# *Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties*





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# Biochar production and applications in sub-Saharan Africa: opportunities, constraints, risks and uncertainties

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## ABSTRACT

Sub-Saharan Africa (SSA) experiences soil degradation, food and livelihood insecurity, environmental pollution and lack of access to energy. Biochar has gained international research attention, but few studies have investigated the potential of biochar to address the challenges in SSA. This paper seeks to identify and evaluate generic potential opportunities and constraints associated with biochar application in sub-Saharan Africa using Zimbabwe as case study. Specific objectives were to; (1) identify and quantify feedstocks for biochar production; (2) review literature on the biochar properties, and evaluate its potential applications in agriculture, environmental remediation and energy provision, and (3) identify research gaps, risks and constraints associated with biochar technology. Biochar feedstocks in Zimbabwe were estimated to be 9.9 Mt yr$^{-1}$, predominantly derived from manure (88%) and firewood (10%). This will yield 3.5, 1.7 and 3.1 Mt yr$^{-1}$ of biochar, bio-oil and synthetic gas, respectively. Land application of the 3.5 Mt yr$^{-1}$ of biochar (≈ 63% C) would sequester approximately 2.2 Mt yr$^{-1}$ of soil carbon in Zimbabwe alone, while simultaneously minimizing the environmental and public health risks, and greenhouse gas emissions associated with solid organic wastes. Biochar potentially enhances soil and crop productivity through enhanced nutrient and soil moisture availability, amelioration of acidic soils and stimulation of microbial diversity and activity. Due to its excellent adsorption properties, biochar has potential applications in industrial and environmental applications including water and wastewater treatment, remediation and revegetation of contaminated soils and water. Biochar products have energy values comparable or higher than those of traditional biomass fuels; thereby making them ideal alternative sources of energy especially for poor households without access to electricity. Before the benefits of biochar can be realised in SSA, there is need to overcome multiple risks and constraints such as lack of finance, socio-economic constraints including negative perceptions and attitudes among both researchers and consumers, and environmental and public health risks. Therefore, there is need to conduct fundamental research to demonstrate the benefits of biochar applications, and develop policy framework and criteria for its production and subsequent adoption.

**Keywords:** Biochar, carbon sequestration, climate change, crop productivity, energy provision, pyrolysis, smallholder agroecosystems, Zimbabwe

## 1. Introduction

Biochar, a carbonized solid by-product of bioenergy production through high-temperature pyrolysis or degasification of organic material under low oxygen conditions, has garnered research attention in recent years (Lehmann et al., 2006; van Zweiten, et al., 2010). However, most of the research on biochar production and its applications has been conducted in the USA, Australia, South America, China and Europe. In these regions, the potential role of biochar in improving soil fertility, soil water-holding capacity and crop yields, while sequestrating carbon and reducing greenhouse gas emissions is well-documented (Sohi et al., 2009; Verheijen et al., 2010). Literature on the agronomic impacts of biochar show enhanced soil fertility and crop productivity, especially where biochar was combined with fertilizers (Kimetu et al., 2008; Lehmann et al., 2002). Enhancing nutrient uptake and use efficiency is particularly important in SSA where most farmers cannot afford chemical fertilizers. On the contrary, neutral or negative plant growth responses have been observed on soils amended with sole biochar (Blackwell et al., 2009; Gaskin et al., 2010). For example, biochar application at 5 and 15 t $ha^{-1}$ reduced soyabean yields by 37% and 71%, respectively (Kishimoto and Sugiura, 1985). In Pennsylvania, Mikan and Abrams (1995) observed that tree density and basal area were reduced by 40% in 100-year-old charcoal hearth areas compared to non-hearth areas. The reduced growth and yield could be attributed to microbial immobilization of nutrients associated with the high C: N ratio especially during the initial phases of biochar amendment. Other studies have demonstrated that fresh biochar amendments do not consistently improve soil conditions, and may cause phytotoxicity (Bernardo et al., 2011; Chan and Xu, 2009). Benefits from biochar amendments are expected to show readily in inherently infertile soils with low organic carbon. The occurrence of surrounding oxisols to the anthropogenic terra preta soils in the Amazon region is one key example (Lehmann et al., 2003). Soils in smallholder cropping systems in sub-Saharan Africa (SSA) are inherently poor, characterised by low pH, low inherent soil fertility and organic matter and low water holding capacity (Nyamapfene, 1991) and thus could benefit greatly from biochar application.

Research on biochar use in Africa is still in its infancy (Torres, 2011; Torres-Rojas et al., 2011). Although some of the studies have been ongoing for several years, evidence on beneficial effects of biochar amendments is still inconclusive. A review by Glaser et al. (2001) of studies on charcoal conducted in the 1980s and 1990s showed marked improvements in soil quality and crop productivity at low charcoal additions (0.5 t $ha^{-1}$). Higher rates inhibited crop productivity. In a field study conducted on degraded light (11-14% clay) and heavier (45-49% clay) textured ultisol soil, addition of wood biochar (6 t C $ha^{-1}$) derived from *Eucalyptus saligna* more than doubled maize yields in West Kenya (Kimetu et al., 2008).On a similar Ultisol soil in Kenya, Torres (2011) showed that pyrolysis of nutrient-rich feedstocks had no significant effects on crop growth but the opposite was true for nutrient-poor feedstocks such as maize cobs. Several reviews on biochar have been conducted in Australia (Sohi et al., 2009), Europe (Verheijen et al., 2009), India (Singh and Gu, 2010) and elsewhere (Glaser et al., 2002; Woolf et al., 2007). In comparison, there is a dearth of similar comprehensive studies documenting the potential opportunities and constraints of biochar production and applications in Africa, particularly SSA. SSA is plagued by a myriad of issues including food insecurity, malnutrition, land degradation, poverty, HIV-AIDS, high population growth, insufficient energy and water, poor sanitation and impacts of climate change (Giller et al., 2009; Rockström, 2003). Consequently, studies (Rockström et al., 2009) suggested that, due to these inter-related developmental challenges, achieving the Millennium Development Goals (MDGs) in the region is doubtful. The current review applies a conceptual framework analysis and critical review of existing global scientific literature to explore the broad research question; *Is biochar the panacea for some of Sub-Saharan Africa's developmental challenges?*

In this paper, we explore the potential benefits of biochar and its co-products in SSA. However, we contend that several constraints, risks, and knowledge gaps pertaining to biochar production and its use in SSA still exist. The specific objectives of this paper are; (1) identify and quantify feedstocks for biochar production; (2) review literature on the biochar properties, and evaluate its potential applications in agriculture, environmental remediation and energy provision, and (3) identify research gaps, risks and constraints associated with biochar technology.

## 2. The case for biochar in sub-Saharan Africa

Rapid population growth and the increasing demand for food and energy have contributed to land degradation in SSA (Dreschel et al., 2001; Rockström et al., 2009). These self-reinforcing interactions or feedbacks of population growth, land degradation and food security create a vicious cycle of poverty among smallholder farmers in SSA. Calls to address the situation advocate for a green revolution in SSA, involving at least a doubling of crop yields over the coming decades (Rockström et al., 2009). Previous and current efforts have focused on improving soil fertility through use of fertilizers, and improving soil moisture availability through water harvesting systems (Rockström et al., 2009). To date, missing in the discourse to improve food security, livelihoods, energy production, water conservation and sanitation and climate change mitigation in SSA is a biochar technology.

Smallholder crop production in SSA is practised predominantly on infertile sandy soils derived from granitic parent material. These soils have poor water holding capacity and low and declining soil fertility and are naturally acidic (pH < 4.3) (Nyamapfene, 1991).

Consequently, crop yields are very low, averaging about 1 t $ha^{-1}$ for most grain crops (Rockström et al., 2003). Land degradation as a result of soil erosion, deforestation, acidification, soil organic carbon depletion, desertification and environmental pollution is prevalent in SSA. Smallholder farmers lack access to electricity, and hence rely on biomass for cooking and heating. Combustion of biomass in traditional stoves poses significant health and environmental risks particularly to women and children. The use of biomass for energy provision deprives the soil of organic carbon required for maintaining soil productivity. These challenges create an ideal setting to develop and evaluate biochar. Coupling biochar production for use as a soil conditioner to energy provision for cooking and heating represents one option to complement current efforts to enhance food and livelihoods security, and environmental quality in SSA. Fig. 2 presents an overview of the potential feedstock for biochar production, pyrolysis methods, potential applications and impacts of biochar in SSA. Also evident in Fig. 2 are some of inconsistent impacts and knowledge gaps on biochar in SSA.

### *2.1. Biochar feedstocks*

The choice of feedstock biomass for biochar production depends on local availability of material and cost of acquisition including haulage costs. Feedstocks in Zimbabwe and other countries in SSA include crop residues, manure, wood wastes from forestry, wastes from agro-processing industries, aquatic weeds and municipal solid wastes and sewage sludge. Major feedstocks and their estimated quantities are listed in Table SM1 in Supplementary Material. Here, we highlight specific examples of the different feedstocks and provide some estimates of the quantities available.

Natural vegetation in SSA is predominantly savannah woodlands and grasslands. Compared to arid and semi-arid regions, savannah vegetation exhibits rapid growth due to a wetter tropical climate. These materials and their by-products are potential feedstocks for biochar production. While the harvesting of such biomass for biochar production may be considered unsustainable, frequent fires experienced in the savannah imply that most of this biomass act as fuel load. The burning of such biomass releases substantial quantities of greenhouse gases causing climate change. Although the total amount of biomass and annual productivity is difficult to estimate, the amount available is substantial. This biomass is a key source of energy for household heating and cooking. Pyrolytic cookstoves produced about 0.5 t of biochar per household per year (Torres, 2011). Based on a rural population of 8 million in Zimbabwe (FAOSTAT, 2013) and an average of eight people per household (Torres, 2011), pyrolytic cookstoves have the capacity to produce approximately 500 000 t of biochar per year.

The Zimbabwean economy is dominated by agriculture specifically crop production, forestry and livestock production. Annually, Zimbabwe produces approximately 1.6 million tons of cereals, 0.7 million tons of oil seeds, 0.3 million tons of root and tuber crops and 0.3 million tons of citrus and other fruits (FAOSTAT, 2013). Besides crop production, Zimbabwe also has a thriving forestry industry, producing more than 1.3 million $m^3$ per year of roundwood and other forestry products (FAO Yearbook, 2012; FAOSTAT, 2012). Farm-level primary processing and secondary agro-processing of these crops generate substantial amounts of wastes. Data from sawmills indicate that 44% of wastes were generated per every tonne of roundwood milled. Based on a conservative product to waste ratio of 50%, crop residues (e.g. husks, cobs) and agro-processing solid wastes constitute substantial quantities of feedstocks for biochar production. If not used for biochar production, the disposal of such wastes poses significant public health and environmental risks.

Manure is another potential feedstock for biochar production (Lehmann et al., 2012). In this regard, biochar from cattle and poultry manure has been widely studied as a soil conditioner (Chan et al., 2008; Steiner et al., 2007). In 2010, Zimbabwe had 5 million head of cattle and 3 million head of goats and sheep and 33 million heads of poultry estimated from the commercial sector. Daily manure production rates are estimated to be about 30 – 55 kg per head for cattle, 10-35 kg per head for goats, sheep and pigs and 0.1 kg per head for poultry with dry matter content of 13-15% (Brandjies et al., 1986). This yields dry matter manure production of 3.9, 1.3 and 0.013 kg per head per day for cattle, goats and chickens, corresponding to approximately 1424, 475 and 5 kg per year, respectively. This will give an estimated 8 697 585 t $yr^{-1}$ dry matter.

Most cities in Zimbabwe and other countries in SSA have centralized systems for wastewater treatment and municipal solid waste management. These cities often have high population densities, and solid waste disposal is a major environmental problem. According to FAOSTAT (2012), the current estimated urban population is 5.3 million and accounts for about 40% of the national population. About 97% of this total urban population have access to water and wastewater and refuse collection system services, while the remainder are in informal settlements with no such services (Thebe and Mangore, 2012). On this basis, about 588 000 $m^3$ of wastewater is generated daily by the urban population. Using a 30 kg sludge per capita per day (UN-Habitat, 2008), and the assumed 97% of the total urban population connected to the sewer system, total annual sludge production was estimated to be 0.15 Mt $yr^{-1}$. Similarly, assuming a municipal solid waste generation of 4 kg per person per day, we can also estimate the total amount of municipal solid waste (MSW) generated in each of the major cities and the total. In Ghana, Duku et al. (2010) estimated that organic wastes constitute about 68% of the municipal solid waste. Using this value and population data, the total amount of biochar feedstock from MSW was estimated.

Using sludge as a feedstock will restrict build-up of stockpiles of sludge and associated environment pollution, while simultaneously providing other benefits.

Environmental and public health risks associated with poor sludge and wastewater disposal are well documented in Zimbabwe. These include eutrophication of surface water bodies, and contamination of groundwater and soils (Gwenzi and Munondo, 2008). For example, severe eutrophication of Lake Chivero, a lake that supplies water to the capital city Harare caused by N and P inflows from wastewater and sludge promote excessive growth of aquatic weeds such as water hyacinth and algae.

In summary, Zimbabwe produces approximately 9.9 Mt $yr^{-1}$ of biochar feedstock per year, 98% of it in the form of manure (8.7 Mt $yr^{-1}$) and firewood (1.0 Mt $yr^{-1}$). Using pyrolytic cookstoves (for firewood) and slow pyrolysis reactors will potentially produce approximately 3.5 Mt of biochar, 3.1 Mt of syngas and 1.7 Mt of bio-oil annually. These estimates are conservative because they exclude other potential biochar feedstocks in Zimbabwe such as algae and water hyacinth, wastes from sugarcane, grasses, and faecal matter and domestic solid wastes from rural areas and informal settlements. Although the total biomass in eutrophic water bodies in Zimbabwe is yet to be quantified, they constitute potential feedstocks for biochar production. Preliminary laboratory studies using biochar derived from water hyacinth as an adsorbent indicate that the biochar removed about 90% of heavy metals in aqueous solution (Gwenzi et al., 2014). Therefore, the development of biochar from aquatic weeds, and its subsequent applications in agriculture and industrial processes is a beneficial and environmental friendly and innovative method for controlling the aquatic weeds. It is noteworthy that most of these biochar feedstocks have high water content. Several methods to reduce the water content including deep drying have been investigated (e.g. Westerhof et al., 2007), but may increase energy requirements and consequently greenhouse gas emissions (Sohi et al., 2008).

*2.2. Appropriate biochar production systems in sub-Saharan Africa*

Thermochemical conversion of biomass into biochar, bio-oils and synthetic gas can be achieved through pyrolysis, carbonization and gasification (Brown, 2009; Singh et al., 2010). Based on reactor temperature, pyrolysis can be broadly classified into gasification (>800$^{o}$C), slow (450-650$^{o}$C) and fast (~500$^{o}$C) (Brown, 2009; Sohi et al., 2009). To optimize the production of biochar relative to other pyrolysis products, slow pyrolysis is most appropriate (Duku et al., 2011). Fast pyrolysis and gasification are most appropriate for optimizing the production of bio-oil and synthetic gas (syngas), respectively.

Pyrolysis reactors can be operated in continuous and batch modes. Typical continuous pyrolysis reactors include fixed- and fluidized-bed pyrolysers, auger/screw type pyrolysers and rotary kilns (Fig. 3). These reactors involve continuous input of feedstock and output of biochar, bio-oil and syngas, and often results in higher biochar yields and operational efficiencies than batch processes (Brown, 2009; Downie et al., 2009). Compared to batch reactors, continuous reactors are more complex and expensive to design and operate, and may require a reliable source of electricity (Brown, 2009; Duku et al., 2012). Therefore, continuous reactors are ideal for medium to large scale biochar production systems relying on centralized large quantities of feedstock.

Batch reactors include traditional charcoal production systems such as pits, earth mound, and brick, metal and drum kilns (Fig. 4) and various designs of pyrolytic cookstoves (Fig. 5) (Torres, 2011; Torres-Rojas et al., 2011). In batch reactors, the thermochemical processes occur at temperatures above 300$^{o}$C, and continues by itself giving off considerable heat with a maximum temperature of approximately 500$^{o}$C (FAO, 1983). Batch reactors are easier to design and operate, and are based on simple and cheap technology (Brown, 2009). However, their operational inefficiency leads to low biochar yields, no heat recovery and significant feedstock burn off (Duku et al., 2011). In Kenya, Ghana and Zambia where biochar and charcoal are produced by small-scale users, earth mound kilns and drum kilns are commonly used (International Biochar Initiative, 2013).

In Zimbabwe, the prevalence of sparsely settled small-holder farmers with low technical skill in biochar production and low capital would favour batch reactors. A low-cost metal drum batch reactor has been designed and fabricated from locally available materials (Fig. 4C). The system consisted of insulated drum kiln housing a 200-l drum closed on both ends for producing biochar for research purposes. Temperatures in the metal kiln ranged between 300-500$^{o}$C when the reactor was operated using cattle manure as a feedstock. Recent pilot studies in Kenya have evaluated the Anila pyrolytic cookstoves as low-cost batch reactors (Torres, 2011; Torres-Rojas et al., 2011). The pyrolytic cookstoves required less biomass and were more energy efficient than traditional three-stone biomass stoves, and reduced wood energy consumption by 27% while producing an average of 460 kg ha$^{-1}$ yr$^{-1}$ of biochar (Torres-Rojas et al., 2011). Compared to traditional three-stone open fire cookstoves and burning of biomass, pyrolytic cookstoves minimize environmental and public health problems due to reduced air pollution and emissions of greenhouse gases (Whitman et al., 2011). Considering that biomass is the main source of energy for heating and cooking among poor households, coupling biochar production for use as a soil conditioner to household energy provision seems attractive in SSA. This approach is likely to promote more biochar adoption than stand-alone pyrolysis systems meant solely to produce biochar for soil application.

*2.3. Biochar properties and multiple applications*

Biochar properties are highly variable, and are determined by type of feedstock and pyrolysis process and conditions. Table SM2 in Supplementary Material summarizes the physical and chemical properties of biochar. Biochar produced at low temperature may be suitable for controlling fertilizer nutrients release (Day et al., 2005), while high temperatures would yield material similar to activated carbon (Ogawa et al., 2010). Due to the high aromaticity, carbon in biochar is highly recalcitrant in soils, with reported residence times in the range of 100s to 1,000s of years, which is approximately 10 to 1,000 times longer than the residence times of most soil organic matter (Verheijen et al., 2010). Therefore, biochar incorporated in soil represents a potential terrestrial carbon sink and also a means of mitigating $CO_2$ emissions. Cation exchange capacity (CEC) of biochar range from 8 $cmol_c$ $kg^{-1}$ to 40000 $cmol_c$ $kg^{-1}$ and has been reported to increase with time following incorporation in soil (Verheijen et al., 2010). This increase in CEC with aging reflects an accumulation of carboxylic functional groups occurring after exposure to oxygen (Lehmann, 2007; Verheijen et al., 2010). The water holding capacity (WHC) of biochar ranges from 75 to 247% (Solaiman et al., 2012). Biochar water retention and adsorption capacity are influenced by its macropore structure and pore size distribution (Ogawa et al., 2010; Yu et al., 2006). Other factors influencing the adsorption-desorption behaviour of biochar include pH, CEC, surface group functionality, and surface heterogeneity (Amonette and Joseph, 2009; Gaskin et al., 2008).The WHC and CEC are crucial for enhancing water and nutrient retention and their bioavailability particularly in inherently infertile sandy soils predominant in the smallholder cropping systems in SSA. Slow pyrolysis biochar produced in the presence of steam tend to be acidic, while fast pyrolysis biochar produced in absence of steam tend to be very basic and make good liming agents (Hass et al., 2012). However, in general, the pH of biochar is typically neutral to basic and relatively constant, thereby neutralizing highly acidic tropical soils. Studies have documented the capacity of biochar to ameliorate acidic soils (Gaskin et al., 2010; van Zwieten et al., 2010). Biochar also contains nitrogen, phosphorus and basic cations (Ca, Mg and K), which are essential plant nutrients (Major et al., 2010).

The application of biochar as an adsorbent for the removal of neutral, anionic and cationic contaminants (Cao et al., 2009; Yao et al., 2011) is derived from its high internal specific area arising from its high porosity and irregular internal structure, and partly due to surface charges (van Zwieten et al., 2009; Zhang et al., 2011). Biochar porosity increases significantly with increasing production temperature, leading to increases in specific surface area from less than 10 $m^2\ g^{-1}$ at production temperatures below 400°C to as much as 400 $m^2\ g^{-1}$ at production temperatures of 550–600°C (Brown, 2009). Biochar also has high heating values (HHV) comparable or even higher than that of conventional biomass fuels such as wood and coal (Tables SM2 and SM4 in Supplementary Material). In this regard, biochar briquettes and stoves have been developed in Kenya and Uganda (IBI, 2012).

### *2.3.1. Soil quality*

Properties of biochar such as its high surface area and cation exchange capacity (CEC), low bulk density, neutral to alkaline pH, high carbon content, high stability and nutrient content (Table SM2 in Supplementary Material), make it an ideal soil conditioner for tropical clay and sandy soils in SSA. As demonstrated by Liang et al. (2006), application of biochar to soils will enhance CEC, nutrient retention and bioavailability. Several other studies have reported improved bioavailability and plant uptake of nutrients following biochar application on different soils (Hass et al., 2012; Uzoma et al., 2011). This aspect is particularly important for sandy soils which have a high potential for nutrient leaching. For example, using a column experiment, Laird et al. (2010) observed that addition of biochar at a rate of 20 g $kg^{-1}$ to a loamy soil reduced leaching of total N and total dissolved P by 11% and 69%, respectively. On acid soils with typical pH values of 4.5-5.0, application of neutral and alkaline biochar has the potential to neutralize acidity, improve nutrient availability and ameliorate aluminium toxicity (Sika and Hardie, 2013; Hass et al., 2012).

Biochar with low density (300 kg $m^{-3}$) and highly stable organic carbon to soils has the potential to reduce bulk density and penetration resistance, and hence increase total soil porosity. This biochar function is particularly important on soils with high dry soil bulk density and penetration resistance due to natural causes or poor management. Degraded Zimbabwean soils with poor soil structure could benefit from biochar amendments. Both crusting and self-sealing soils are common in some of the major soils used for production of major field crops in Zimbabwe (Gwenzi et al., 2009). Biochar application enhances aggregation and aggregate stability (Mukherjee and Lal, 2013). Although the mechanisms are poorly understood, some studies have proposed that enhanced root growth, mycorrhizal fungi and production of waxes and mucilages bind soil particles together (Mukherjee and Lal, 2013). The highly stable organic carbon in biochar may also play a critical role in improving soil aggregation and aggregate stability. Overall, changes in soil structure due to biochar application may enhance soil moisture retention, infiltration, and consequently reduce runoff and erosion.

Data also show that biochar application improved soil biological properties. The morphology and heterogeneity of pore size distribution in biochar provides a habitat for soil organisms and protects them from predation and desiccation (Rillig et al., 2010; Thies and Rillig, 2009). Enhanced microbial diversity and activity including enzymatic activity and respiration have also been observed on biochar-amended soils (Steiner et al., 2008). For example, a 100% increase in root colonization by arbuscular mycorrhizae was observed following application of biochar at a rate of 3% (Elmer and Pignatello, 2012). Increased biological nitrogen fixation by common beans (*Phaseolus vulgaris* L) has also been reported following biochar application (Rondon et al., 2006). Other studies showed that biochar application to soils induced systemic plant resistance to pathogens and diseases (Elad et al., 2010; Elmer and Pignatello, 2012). A greenhouse study involving addition of biochar at 1.5 and 3.0% on a weight basis to a field growing asparagus significantly reduced root lesions caused by *Fusarium oxysporum* f. sp. *asparagi* and *F. proliferatum* compared to the control (Elmer and Pignatello, 2012). Elad et al. (2010) showed that, 105 days after biochar application, pepper powdery mildew was significantly less severe in the biochar-treated plants compared to the control without biochar. Although there are a few exceptions documenting negative impacts on mycorrhizal (Warnock et al., 2010), the bulk of the evidence suggests that biochar stimulates microbial abundance, diversity and activity. The changes in microbial diversity and activity due to biochar application may in turn cause changes in nutrient transformation and overall soil biogeochemistry. A review of impacts of biochar on soil biology is presented in Lehmann et al. (2011).

### *2.3.2. Crop productivity*

Poor seed emergence constitutes a major constraint to crop production for smallholder farmers in the semi-arid tropics (Murungu et al., 2003). The improvements in soil quality associated with biochar application have often resulted in enhanced seed emergence, crop growth and productivity. Biochar application has been reported to enhance crop emergence and establishment (e.g. Solaiman et al., 2012; van Zwieten et al., 2010). A laboratory bioassay by Solaiman et al. (2012) demonstrated that biochar type and application rates had a significant effect on germination and early growth of wheat, mung beans and clover. Similarly, van Zwieten et al. (2010) showed that wheat seed germination was increased with a single dose (10 t $ha^{-1}$) of paper mill biochar. The mechanisms involved may include improved moisture retention and availability, and reduced soil bulk density. Therefore, biochar application may overcome poor emergence and crop establishment caused by soil crusting, and sealing, and inadequate soil moisture, all conditions common to Zimbabwean sandy soils.

In most smallholder cropping systems in SSA, crop yields are generally low (1 t $ha^{-1}$) due to a combination of low and declining soil fertility, unavailability of fertilizers and limited soil moisture caused by mid-season dry spells and droughts (Rockström et al., 2003). Biochar can play a critical role in mitigating against these adverse conditions. Increased crop yields due to biochar application have been observed in several field studies (Table SM3 in Supplementary Material). In SSA, a few studies have also reported yield increases following biochar application (e.g. Kimetu et al., 2008). In Zambia, maize yield increases between 80% and over 400% were observed on biochar amended soil relative to the control (Cornelissen et al., 2013). On a degraded tropical soil in Kenya, Kimetu et al. (2008) demonstrated that biochar has the capacity to restore soil quality and crop productivity, resulting in about 2.9 tonnes more yield on biochar amended soil than control plots with fertilizer but no biochar (Kimetu et al., 2008). These yield increases are also associated with increases in nutrient and water use efficiencies (Utomo et al., 2011). Enhancing resource use efficiency is particularly important in smallholder agroecosystems, where losses of both water and nutrients via runoff and deep drainage are often high. In Ghana, Yeboah et al. (2009) reported up to 5% increase in N recovery when biochar was applied to maize fields on a sandy soil. This was attributed to nutrient retention. An increase in nutrient uptake of 100 kg K $ha^{-1}$, 10 kg Mg $ha^{-1}$ and 5 kg Ca $ha^{-1}$ was observed in maize in Columbia (Major et al., 2010). This was accompanied by a progressive maize yield increase from 28% to 140% over 4 years (Major et al., 2010). In a study by Lehmann et al. (2003), a 70% increase in cowpea biomass production was noted compared to control with no biochar application. These increased crop yields were attributed to the liming effect of the biochar, increased availability of Ca and Mg, proliferation of N fixing bacteria in leguminous crops, and nutrient and water retention and bioavailability (Lehmann et al., 2003; Major et al., 2010). In summary, given that carbon in biochar is not directly taken up by plants, the impact of biochar on crop productivity is largely through improvements in soil physical, chemical and biological properties (Section 2.3.1).

The production of large quantities of biochar using batch reactors such as locally fabricated kilns and pyrolytic cook stoves could be a challenge to most smallholder farmers. In view of this limitation, we propose that initial biochar application be limited to small niches such as horticultural crops, urban and peri-urban agriculture, household nutrition and herbal gardens and cultivated wetlands. In particular, small gardens for peri-urban and rural households provide an ideal niche to test and demonstrate the benefits of biochar on soil fertility, water retention and hence crop yields. In SSA's savannah ecosystems, wetlands are used for vegetable gardens, which play a critical role in food security and household income under rainfed conditions in SSA. Biochar application to wetland soils could have a stabilization effect on possible degradation of the wetland while enhancing crop production and mitigating greenhouse gas emissions and nitrogen leaching.

### *2.3.3. Clean and high-value energy source*

About 53% of total energy demand in SSA (about 267 MW) was derived from traditional fuels such as unprocessed biomass, while the remainder is from oil (26%), solid fuels (24%), hydroelectricity (3%) and gas (2%) (FAO, 1994). Biochar, bio-oils and synthetic gas from pyrolysis are also potential sources of energy and industrial raw materials. Bio-oil is an energy source (17 MJ $kg^{-1}$), which can be burned to provide energy for heating or can be refined to transportation fuels (Laird, 2008). Like bio-oils, syngas can be used to heat the pyrolyser or provide energy for household and industrial uses. For any given feedstock, the calorific value of biochar (16-35 MJ $kg^{-1}$) is similar to, or about two times higher than that of the raw biomass and most grades of coal (Mullen et al., 2009; Sohi et al., 2009; Sukiran et al., 2011). Pyrolysis products have similar or higher calorific values (HHV) compared to most traditional energy sources such as firewood, charcoal, coal and coke (Table SM4 in Supplementary Material). Therefore, although most biochar proponents advocate for biochar application to soils, there is also a potential to use it as an energy source (Laird, 2008). Compared to fossil fuels, energy from the three products of pyrolysis are carbon neutral or negative, making them ideal energy sources for the future (Laird, 2008). Moreover, while combustion of firewood, paper and plastic wastes is known for emitting dioxins, no experimental evidence has confirmed dioxin emissions from pyrolysis of traditional biomass feedstocks and the resulting co-products (Sohi et al., 2009; Verheijen et al., 2010). Furthermore, in SSA where most people are not connected to the hydroelectric grid, and rely on biomass energy, pyrolysis bioenergy provides opportunities for more efficient energy production than wood burning (Demirbas, 2004b). It also widens the options for the types of biomass that can be used for generating energy, going beyond wood to include, for example, crop residues. The main benefit may be that pyrolysis offers clean heat, which is needed to develop cooking technology with lower indoor pollution by smoke (Bhattacharya and Salam, 2002) than is typically generated during the burning of biomass (Bailis et al., 2007).

Besides agriculture, the high dependence of urban and rural households on firewood and charcoal for cooking in SSA is also a key driver of deforestation particularly in densely populated areas (Chidumayo and Kwibisa, 2003). In arid and semi-arid areas, wood harvesting for firewood and charcoal is further exacerbated by the inherent low biomass production potential. In SSA, crop residues and animal dung, by-products of agriculture and livestock-related activities are already used to provide a significant proportion of household energy needs (FAO, 1983). The energy and synthetic gas produced during biochar production can be used for cooking and heating at household level. Biochar produced in the process can be applied to the soil. Pyrolytic cookstoves are currently being tested in parts of SSA (Torres, 2011). The use of energy from pyrolysis products can be amenable to both decentralised systems such as household, community and institutional levels. In addition, syngas and bio-oils can be used to produce steam to drive turbines in a centralized hydroelectric power station (Laird, 2008). According to historical data, biomass (60%), oil products (17%) and coal (16%) are the main sources of energy for the agricultural sector, the bulk of which is used for agricultural processing (FAO, 1983). Therefore, the availability of feedstock within close proximity to agricultural processing plants makes biochar, bio-oils and syngas attractive sources of energy for agro-industries.

*2.3.4. Disposal of domestic and industrial organic wastes*

In most SSA countries, solid wastes from agriculture, agro-industrial processing, municipal and domestic and sludge from wastewater treatment plants have little or no market value, making their disposal uneconomic. Due to the low value of biomass, and long haulage distances between source and potential markets, the majority of organic wastes are left to decay on-site, dumped in open spaces, landfilled or incinerated (McElligott et al., 2011). These waste disposal strategies cause significant water and air pollution. Recently, a number of countries in SSA including Ghana and Zimbabwe have been promoting the use of landfills and incinerators for disposal of organic wastes (Duku et al., 2011; Government of Zimbabwe, 2002). Landfills and incinerators are costly, while the anaerobic decomposition of organic matter in landfills releases methane, a highly potent greenhouse gas (GHG). On the other hand, incineration of organic wastes is an energy-intensive waste disposal technique and a waste of potential energy, which also releases atmospheric pollutants and greenhouse gases (McElligott et al., 2011). In this regard, the pyrolysis of these organic wastes to produce biochar, bio-oils and syngas presents an emerging market for organic wastes. Compared to landfills and incineration, separation at source, and subsequent pyrolysis of organic wastes has numerous environmental benefits; (1) unlike landfills and incinerators, pyrolysis is carbon neutral or negative, hence reduces GHG emissions and energy requirements, respectively, (2) pyrolysis reduces air and water pollution associated with leachate and odours from waste dumps and landfills, and (3) the products of pyrolysis (biochar, bio-oils and syngas) have numerous potential applications in energy supply, remediation of contaminated soils and water and wastewater treatment. The use of biochar for wastewater treatment in decentralised systems provides an attractive option for improving sanitation in informal urban settlements, rural communities and institutions such as hospitals and schools. Most importantly, biochar application to soils enhances soil quality and crop yields on marginal soils, while minimizing nutrient leaching and greenhouses gas emissions (Laird et al., 2010; Zhang et al., 2011).

*2.3.5. Carbon sequestration and mitigation of greenhouse gas emissions*

Crop and animal production systems contribute considerably to climate change, accounting for approximately 5.1 to 6.1 Gt $CO_2$ eq $yr^{-1}$ (10-12%) of the total annual global anthropogenic emissions (Smith et al., 2006). The incorporation of biochar in smallholder and commercial agroecosystems in SSA will be consistent with the global thrust to sequester soil carbon and reduce emissions of greenhouse gases. In SSA, biochar will complement management practices promoting a shift from tillage to no-till systems through conservation agriculture (Knowler and Bradshaw, 2007; Rockström et al., 2009). Besides improving soil quality and productivity, biochar has both direct and indirect impacts on greenhouse gas emissions (Mukome et al., 2013). The direct impacts include the stabilization and sequestration of carbon in the soils. Using an estimated biochar carbon content of 63%

(Graber and Hadas, 2009; Laird, 2008) and annual biochar production of 3.5 Mt (Table SM1 in Supplementary Material), biochar land application would potentially sequester about 2.2 Mt $yr^{-1}$ of soil carbon in Zimbabwe alone. Compared to ordinary soil carbon characterized by high turnover and release of $CO_2$, carbon in biochar is more recalcitrant to decomposition (Lehmann et al, 2006; Zimmerman, 2010). Therefore, transforming biomass into biochar diverts carbon from the rapid biological cycle into a much slower biochar cycle (Lehmann, 2007). In addition, converting waste biomass into biochar reduces potential methane and $CO_2$ emissions from landfill and waste dumps (Ackerman, 2000).

Improved nutrient and water retention implies enhanced resource use efficiency. The resulting energy savings and irrigation costs arising from reduced irrigation frequency and fertilizer use will in turn reduce greenhouse gas emissions (Sohi et al., 2010). Moreover, several field and laboratory studies have demonstrated the impacts of biochar application on emissions of non-$CO_2$ GHG. Two separate studies conducted on tropical soils showed that biochar application reduced $CH_4$ emissions on a grassland and soyabean crops relative to the control (Rondon et al., 2005; 2006). In an incubation study by Yanai et al. (2007), municipal waste biochar decreased emission of $N_2O$ by over 500% as compared to the control. Application of biochar to composting poultry litter reduced ammonia emissions by up to 64% and total N losses by up to 52% (Steiner et al., 2010). Significant reductions in $N_2O$ and $NH_3$ emissions have also been reported following biochar application to soils treated with ruminant urine (Taghizadeh-Toosi et al., 2011). The reduction of emission of these gases occurs via enhanced nitrification (Berglund et al., 2004). Possible mechanisms include biochar adsorption of nitrifier-inhibitory compounds like phenolics and suppression of the activity of substrate ($NH_4^+$-N)-competing microorganisms, and a promotion of the proliferation of nitrifiers (Berglund et al., 2004; van Zweiten et al., 2010). Overall, besides a few exceptions reporting increased $CO_2$ emissions in biochar amended soils, the bulk of existing evidence indicate that biochar application has the potential to mitigate greenhouse gas emissions. However, most of these studies except a few (Rondon et al., 2005; 2006) were conducted under temperate conditions, and it remains unknown whether such results are applicable to the tropical conditions in SSA. Tropical soils experience highly seasonal wet and dry cycles and temperature fluctuations, which could potentially stimulate higher greenhouse gas emissions than in temperate soils.

*2.3.6. Environmental remediation*

The large surface area, cation exchange capacities and neutral to alkaline pH of biochar make it ideal for remediation of contaminated media. Biochar has numerous potential applications in water and wastewater treatment, remediation of contaminated soils and water, restoration and revegetation of degraded soils and artificial landforms such as mine tailings and slimes. A summary of some of the recent studies documenting the removal of organic and inorganic contaminants is presented in Beesley et al. (2012). The review showed that biochar removes polyaromatic hydrocarbons, organic pesticides (Diuron, Atrazine, Dieldrin) and reduced heavy metal bioavailability (Beesley et al., 2012). However, Beesley et al. (2012)'s review excluded the potential role of biochar in remediation and revegetation of contaminated mined sites such as mine tailings and waste dumps. This is particularly important in SSA, where both informal and formal mining is associated with environmental pollution.

Several studies have demonstrated that biochar is highly effective in removal of organic and inorganic contaminants including pesticides and nutrients (Beelsey et al., 2010; Graber et al., 2011). Zhang et al. (2012) reported that adsorption capacities of MgO-biochar nanocomposites were as high as 835 mg $g^{-1}$ for phosphate and 95 mg $g^{-1}$ for nitrate, respectively, far exceeding reported values of other adsorbents. Other studies have shown that adsorption of organic chemicals to biochar greatly exceeded that of humic substances and soil organic matter (Zhang et al., 2006). Studies investigating contaminant mobility in soils further showed the effectiveness of biochar as an adsorbent (Beesley et al., 2010; Cao et al., 2009). These studies clearly demonstrated the ability of biochar to mitigate mobility and toxicity of heavy metals, toxic inorganic and organic contaminants including endocrine disruptors (Winsley, 2007).

In combination with cheap drinking water chlorination systems, biochar can be used as a low-cost adsorbent in water and wastewater treatment in SSA. Given its ability to adsorb both cationic and anionic compounds, biochar may be applied for the treatment of industrial effluent and urban stormwater before discharge into the environment. Industrial effluent and stormwater from highly urbanized areas often contain high concentrations of heavy metals and hydrocarbons. Studies on biochar use as an adsorbent have been largely limited to laboratory studies of heavy metal and nutrient adsorption, but its potential for deflouridation of contaminated groundwater is not known. Despite this drawback, biochar represents a promising and scalable adsorbent for both industrial applications and environmental remediation, because it is cheaper and easier to make than activated carbon. A typical large-scale application may include the development of biochar-based permeable reactive barriers for treatment of contaminated surface and groundwater.

## 3. Biochar constraints, barriers and risks

Biochar faces policy, legal, institutional, technical, financial and socio-economic barriers (Fig. 6). Experience in SSA indicates that the introduction and adoption of new technology is largely dependent on supportive policy and legal frameworks (Karekezi and Kithyoma, 2003), which are in turn driven by benefits of the technology. To our knowledge, most governments in SSA may be unaware of biochar and consequently lack a clear policy or legal framework on biochar technologies. Accordingly, more emphasis will continue to be placed on conventional and proven technologies rather than biochar technology. The lack of public investment in biochar in SSA is a stark contrast to developed countries where large-scale pyrolysis plants are already in operation.

The introduction of biochar and its co-products in SSA requires the development of technical skills at both individual and institutional levels. Currently, there is limited biochar research at national research institutions and universities in SSA. Although some research on biochar is in progress in Ghana, Uganda and Kenya, such research is still in its early stages, and a critical mass of skills and knowledge is yet to be attained. Knowledge outputs from such fundamental research will be critical in shaping the position of biochar in SSA.

As demonstrated by previous efforts to promote renewable energy technologies in SSA (Karekezi and Kithyoma, 2008), the lack of low-cost, long-term financing options is the key barrier to biochar technology generation and adoption. To date the capital outlay, labour and financial requirements required to develop and operate a pyrolysis plant in SSA is unknown. Even when such projects are shown to be viable at pilot scale, accessing bank loans is difficult due to stringent lending conditions.

Perceptions and attitudes also influence the adoption and uptake of new technology especially among risk averse smallholder farmers (David, 1995). Just like biofuels in Africa, there is already immense scepticism and lobbying by some NGOs against biochar production, driven by the misconceptions that, the production of biomass for use as biochar feedstocks will compete for land, labour and inputs, and displace food crops. According to these sceptics, this will culminate in widespread hunger, food insecurity and loss of livelihoods and worsening poverty in regions where 90% of the population is considered poor. These fears are ill-founded as our analysis clearly demonstrated that organic waste material is abundant in

SSA, which can be used a biochar feedstocks. In fact, smallholder farmers are likely to benefit from biochar as evidenced by a few case studies on biochar application to degraded soils (Kimetu et al., 2008) and its use as clean energy source compared to firewood. Whether farmers would be encouraged to grow biomass for pyrolysis appears unlikely but could largely depend on perceived benefits.

Risk and its perception have implications on farmers' decisions and is a determinant of technology adoption particularly among smallholder farmers (David, 1995). Therefore, like conservation agriculture, initial adoption of biochar by farmers is likely to be limited due to perceived risks and farmers' reluctance to change their current practices and embrace new technology. One possibility to enable smallholder farmers to understand biochar and promote its adoption is to relate the benefits to those of traditional slash and burn system, which is familiar to most farmers in SSA. The major contrast is that, while slash and burn system converts biomass to ash through combustion, pyrolysis transforms biomass to biochar, a more stable form of carbon than that in the feedstock. In summary, this entails a shift from the traditional slash and burn practice to slash and char as a feasible alternative for restoration of soil fertility (Lehmann et al., 2002).

Critics of biochar and its co-products contend that the production of biomass feedstock may result in habitat and biodiversity loss and diversion of crop residues from soils. Substantial greenhouse gas emissions from land use conversions, and collection and transportation of feedstocks may also offset the benefits of biochar applications. Poorly engineered pyrolysis plants could also emit potent greenhouse gases, which will degrade air quality, and cause global warming and climate change (Laird, 2008). The arguments have been used for extensive lobbying by environmental activists and skeptics opposed to biochar and biofuels (www.greenfuelwatch.org.uk).

Although empirical evidence is still limited there are also concerns pertaining to the contribution of biochar to particulate emissions during pyrolysis and application. Of major concern are the impacts of particulate black carbon on climate and human health. Biochar application is done by spreading the biochar followed by its incorporation into the soils. The fugitive loss of biochar into the atmosphere constitutes climatic forcing (McElligott et al., 2011). Moreover, in agroecosystems where farmers are already practicing conservation agriculture, the process of biochar incorporation into the soils may stimulate the loss of sequestered soil carbon. The inconsistent impacts of biochar on soil properties, greenhouse gas emissions, carbon sequestration and crop productivity also creates uncertainty about the benefits of the technology, thus highlighting the need for site-specific research.

Concerns have also been raised regarding the potential for soil contamination associated with some biochar constituents. It is crucial to ensure that soil functions and processes as well as water quality are not put at risk as a consequence of biochar application to soils. Contaminants such as polyaromatic hydrocarbons, heavy metals, dioxins that may be present in biochar may have detrimental effects on soil properties and functions (Verheijen et al., 2010). The occurrence of such compounds in biochar is likely derived from either contaminated feedstocks or processing conditions that may favour their production. For instance, slow pyrolysis at temperatures below 500°C is known to favour the accumulation of readily available nutrients in biochar such as sulphur (Hossain et al., 2007). Organic wastes are known to contain high levels of light and heavy metals, which remain in the final biochar product following pyrolysis (Chan and Xu, 2009). Risk assessment for such contaminants is required in order to determine the toxicity of different biochars, safe application rates and operating pyrolysis conditions. Nonetheless, very little experimental evidence is available on the short- and long-term occurrence and bioavailability of such contaminants in biochar and biochar-enriched soil. Moreover, biochar application rates and frequency remain poorly understood. However, biochar applications are, in contrast to manure or compost applications, not primarily a fertilizer, which has to be applied annually. Due to the longevity of biochar in soil, accumulation of heavy metals by repeated and regular applications over long periods of time that can occur through other soil amendments may not occur with biochar.

## 4. Synthesis, recommendations and outlook

The current review revealed that biochar technology has the potential to contribute towards the alleviation of some of the problems in SSA. The paper is meant to stimulate the interest of the regional and international research community and policy makers to consider biochar as a potential technology capable of complementing current efforts. Contrary to current scepticism and concerns about land grabs and competition between food and biochar feedstock production, our data and similar estimates in Ghana (Duku et al., 2012), demonstrated that, indeed SSA has substantial potential feedstocks for biochar production, predominantly derived from sewage sludge, manure, municipal solid waste, and organic solid wastes from agro-processing and forestry.

Decentralised low-cost pyrolyers such drum kilns or pyrolytic stoves that can be designed and fabricated using locally available materials and technical skills appear most ideal for smallholder households in SSA. Biochar production from traditional biomass energy sources such as firewood and crop residues can be coupled to energy provision for cooking and heating, making it an ideal technology for resource-poor households without access to electricity.

However, realizing the multiple opportunities of biochar in SSA requires overcoming financial, socio-economic and technical constraints and barriers. At present, countries in SSA lack the necessary policy and legal framework to develop and promote biochar, understandably due to lack of information on the technology. However, policy incentives such as assigning a monetary value to tangible and intangible benefits of biochar such as reducing the threat of global climate change and enhancing energy security, food security, water quality, and rural economies are vital to unlock public and private investment (Laird, 2008). In SSA and other developing countries, innovative financing mechanisms such as the Cleaner Development Management (CDM) program should include biochar technology. CDM is a program in developed countries that provides financial support to a company in a developing country to undertake programs that reduces greenhouse gas emissions causing global warming and climate change. The other financing option is to develop a viable carbon market where carbon credits can be traded, although the success of such schemes is yet to be evaluated in SSA. In this regard, an opportunity exists under the CDM program for developing countries in SSA to seek funding for biochar research to mitigate climate change and its impacts.

To allay concerns about land grabs, organic solid wastes should constitute the bulk of the biochar feedstocks, while minimizing their environmental and public health impacts. Moreover, local technical capacity and fundamental research information on biochar are required to demonstrate its impact on food security, livelihoods, energy provision and environmental quality. This knowledge gap calls for urgent research and knowledge transfer on biochar to be conducted.

Key research themes on biochar may focus on impacts on soil quality and crop yields, ecotoxicology and greenhouse gas emissions in the dominant agroecosystems in SSA. In addition, research should also focus on development of scalable novel biochar products such as adsorbents for industrial and other environmental pollutants, and biochar-based energy sources such as briquettes, pyrolytic cookstoves, syngas and bio-oils. Engineering research is also needed to design robust and efficient pyrolysers with effective emissions control systems, bio-oil refineries, and agricultural equipment for handling and incorporating biochar into the soil. Socio-economic research is needed to understand stakeholder perceptions, and evaluate the optimum scales for a centralized and distributed network of pyrolysers, and policy and institutional framework for adoption of biochar technology. The outcomes of this research will be critical for policy formulation and allaying fears about the biochar feedstocks, and perceived impacts. Few recent and on-going studies in Kenya (Kimetu et al., 2008), Zambia (Cornelissen et al., 2013), Ghana (Duku et al., 2010), South Africa (Sika and Hardie, 2013) and Zimbabwe (Gwenzi, 2012) provide some of the pioneering research on biochar in SSA. However, there is limited communication and coordination among the research groups working on biochar in SSA. To improve research coordination and exchange of information on successes and challenges among research groups and within the region, we propose the establishment of a regional biochar research initiative that builds on and complements on-going biochar research in SSA. Tasks of the regional initiative could include mobilization of local and international resources, and coordination of biochar research at multiple regional sites to enable comparison of technologies across dominant soil types, agroecosystems and climatic regions in SSA. A regional collaborative research initiative could potentially attract funding in the form of government-to-government international aid support or under the clean development mechanism initiatives. Moreover, the initiative could enable SSA countries to pool local financial resources, research expertise and laboratory facilities, while avoiding duplication of work.

## 5. Conclusions

The review highlights the potential feedstocks, pyrolysis methods and potential applications of biochar in sub-Saharan Africa. It can be concluded that biochar feedstocks are readily available, and technologies for biochar production are largely known. Potential biochar applications include agriculture, mitigation of greenhouse gas emissions, environmental remediation and energy provision. However, biochar could face several constraints including socio-economic barriers, and lack of finance, empirical data and a supportive policy framework. Therefore, future research based on a multi-disciplinary framework should seek to provide a comprehensive understanding of biochar technology, and overcome associated constraints. Overall, the findings of the current review provide a platform for local and international organizations to initiate and support specific research programs on biochar in sub-Saharan Africa.

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**Figure captions:**

**Fig. 1.** Summary depiction of biochar technology in sub-Saharan Africa indicating potential feedstocks (**A**), pyrolysis systems (**B**), potential applications in agriculture, environmental management and energy provision (**C**) and predicted impacts (**D**).

**Fig.2.** Examples of pyrolysis reactor designs for biochar production. (**A**): continuous auger/screw pyrolyser (based on Verma et al., 2012), (**B**): batch insulated drum kiln designed and fabricated in Zimbabwe from locally available materials (Source: Willis Gwenzi) and (C): pyrolytic cookstoves for simultaneous heating and biochar production. **C-1**: A TLUD cookstove in use in Kenya (Photo courtesy of African Christians Organization Network, ACON, http://www.aconetwork.weebly.com), (C-2): Sampada stove (Courtesy of Samuchit Enviro Tech Pvt Ltd, http://www.samuchit.com/) and (**C-3**): Anila stove originally designed by Professor RV Ravikumar of the University of Mysore, India

**Fig. 3.** Barriers to the production and application of biochar and its co-products in sub-Saharan Africa and possible interventions.

**Table captions** (*Supplementary Material*)**:**

**Table SM1** (*Supplementary Material*)

Annual estimates of available feedstocks and quantities of biochar, bio-oil and synthetic gas (syngas) quantities than can be produced in Zimbabwe

**Table SM2** (*Supplementary Material*)

Selected physical and chemical properties of biochar and the related applications

**Table SM3** (*Supplementary Material*)

Effect of biochar application on yields of selected crops

**Table SM4** (*Supplementary Material*)

Comparison of calorific values expressed as higher heating values (HHV) of pyrolysis products to traditional sources of energy

Figure 1
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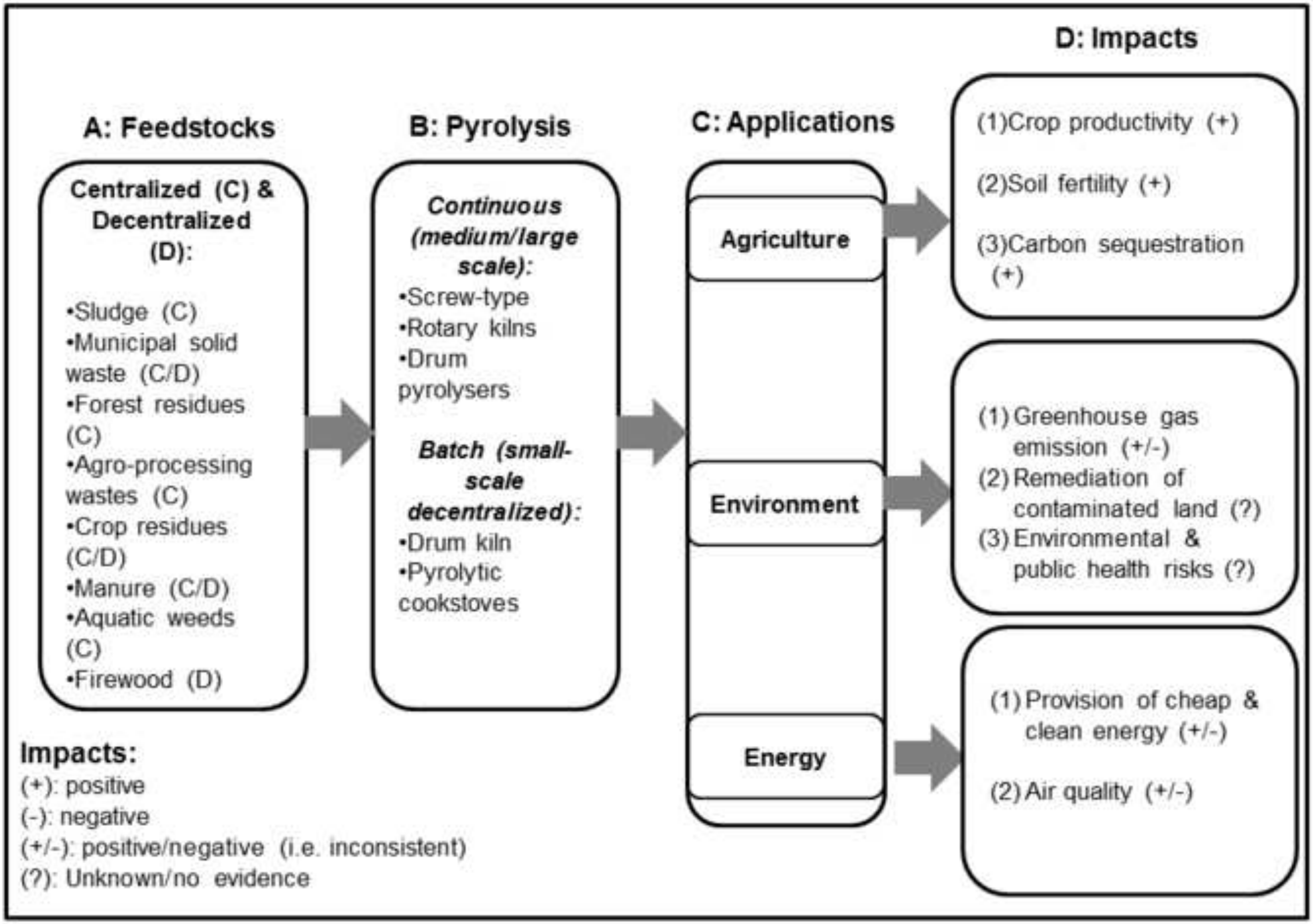


Fig. 1

Figure 2
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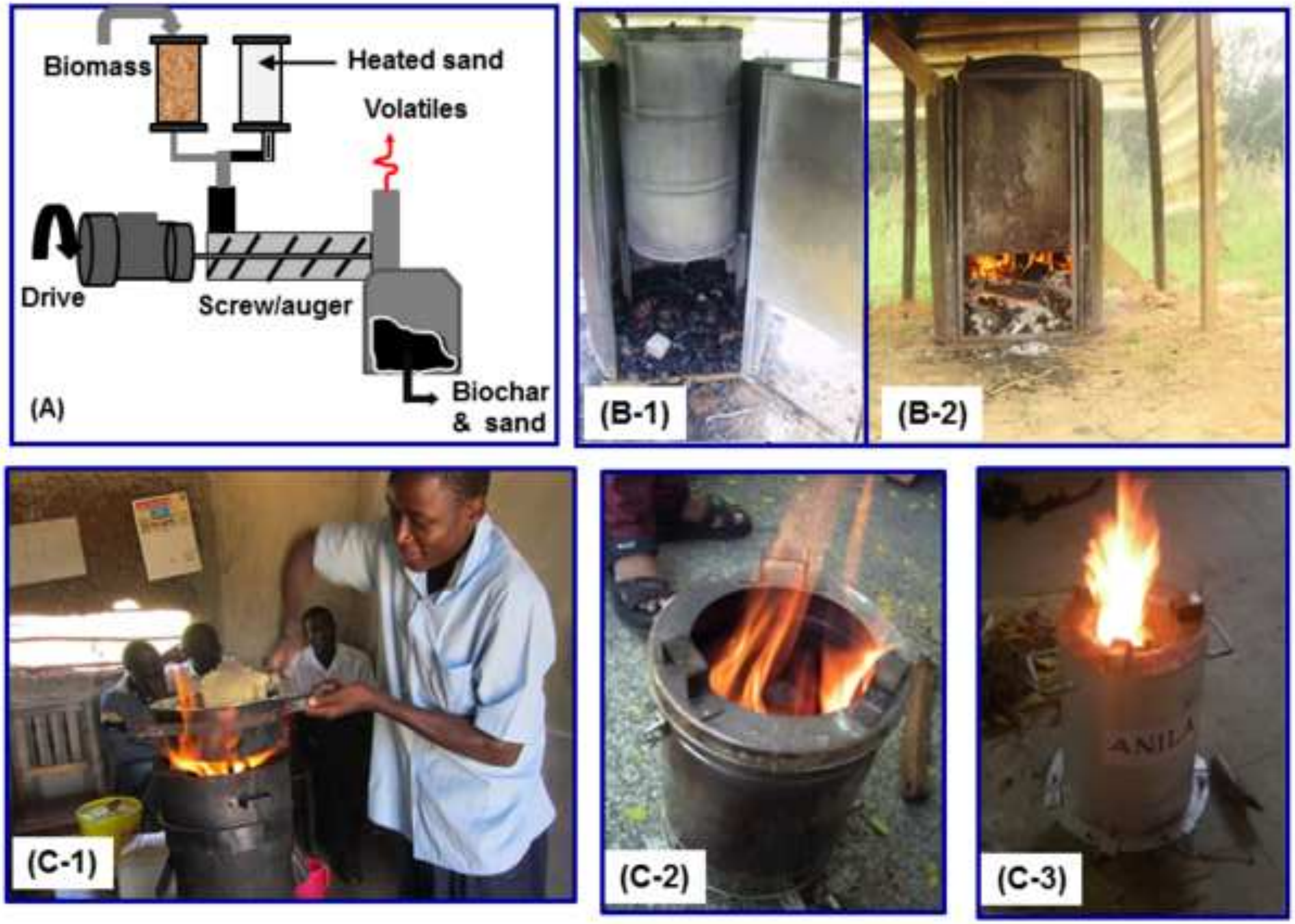

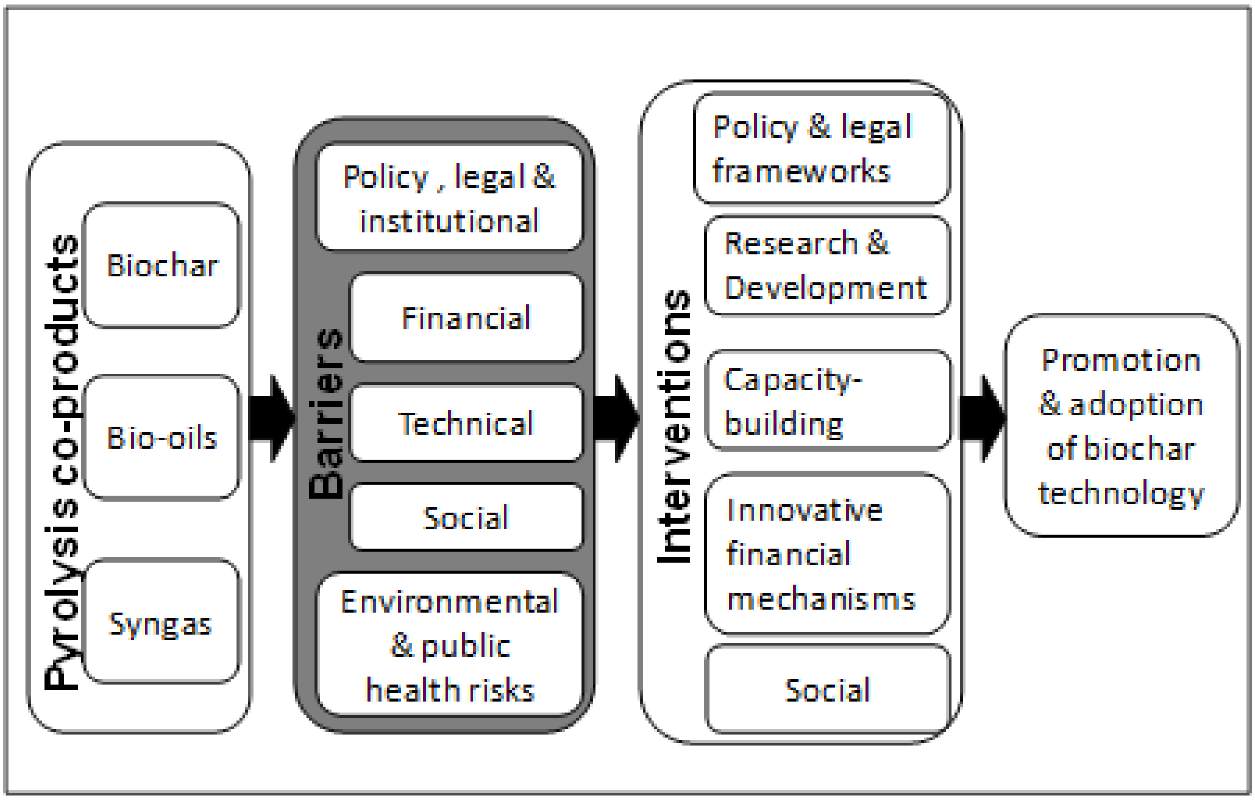
Pyrolysis co-products
Biochar
Bio-oils
Syngas
Barriers
Policy , legal & institutional
Financial
Technical
Social
Environmental & public health risks
Interventions
Policy & legal frameworks
Research & Development
Capacity-building
Innovative financial mechanisms
Social
Promotion & adoption of biochar technology

**Fig. 3**

Table SM1
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**Table SM1** (*Supplementary Material*)

| **Feedstock type** | **Quantity (t yr$^{-1}$)** | **Current practice** | **Biochar yield (t yr$^{-1}$)$^{a}$** | **Bio-oil (t yr$^{-1}$)$^{a}$** | **Syngas (t yr$^{-1}$)$^{a}$** |
|---|---|---|---|---|---|
| Manure | 8,697,585[d] | Stockpiling & land application | 3,044155 | 1,534,868 | 3,044,155 |
| Firewood | 1,000,000[b] | Three-stone stove producing ash | 350,000 | - | - |
| Sewage sludge | 154,230[c] | Stockpiling & land application | 53,981 | 27,217 | 53,981 |
| Municipal solid waste | 14,416[c] | Burning, dumping & landfilling | 5,046 | 2,544 | 5,046 |
| Crop residues | 1,300[d] | Burning, land application & grazing | 455 | 229 | 455 |
| Agro-industry waste | 1,300[d] | Stockpiling, dumping & landfilling | 455 | 229 | 455 |
| Forest residues | 650[d] | Stockpiling & burning | 228 | 114 | 278 |
| Total | 9,869,481 | | 3,454,318 | 1,741,673 | 3,104,318 |

a: Estimates based on slow pyrolysis, which produces 35% biochar, 35% syngas and 30% bio-oil with 70% water (Verheijen et al., 2006).

b: estimated based on Zimbabwe's rural population (FAOSTAT, 2013), average of eight people per household, and feedstock conversion efficiency of about 0.5 and 0.5 t of biochar per household per year using pyrolytic stoves with no recovery of bio-oil and syngas (Torres, 2011; Torres-Rojas et al., 2011).

c: Estimates based population data from FAOSTAT (2013) and Thebe and Mangore (2012) and a daily sewage production per capita 30 kg per capita per day (UN-Habitat, 2008).

d: Estimates based on published production data (FAOSTAT, 2013), manure production per head (Brandjies et al., 1986) and product-to-waste ratios (Aina, 2006; Koopmans and Koppejan, 1997).

**Table SM2** (*Supplementary Material*)

| | **Typical values** | **Application and implications** | **References** |
|---|---|---|---|
| *Physical properties* | | | |
| BET surface area | 43.6-115 $m^2$ $g^{-1}$ | Adsorbent, and nutrient and water retention | van Zwieten et al., 2009; Zhang et al., 2011 |
| Bulk density | 300 kg $m^{-3}$ | Reduced bulk density and improved porosity | Zhang et al., 2011 |
| Stability or residence times | 100s-1000s years i.e. 10-1000 times that of most soil carbon | Increases carbon pool in agricultural soils | Verheijen et al., 2010 |
| Water holding capacity | 75-247% | Improves plant-available water in soils | Solaiman et al., 2012 |
| High heating value (HHV) | 12.8-21.6 | Energy source in form of biochar briquettes or pyrolytic stoves | Brown, 2009 |
| *Chemical  properties* | | | |
| pH ($H_2O$) | Typically neutral to basic (7.6-10.4) | Neutralization or liming of acid soils | Laird et al., 2010 ; Taghizadeh-Toosi et al., 2011; Zhang et al., 2011 |
| Cation exchange capacity (CEC) | Low (8-40 000 $cmol_c$ $kg^{-1}$) but increases with aging | Nutrient and contaminant retention, adsorption of cationic contaminants such as heavy metals | Brown, 2009; Major et al., 2010; Taghizadeh-Toosi et al., 2011; Verheijen et al., 2010 |
| Organic carbon | 293-784 g $kg^{-1}$ | Carbon sequestration and increased CEC | Solaiman et al., 2012; Zhang et al., 2011 |
| Total Nitrogen (N) | 3.2-7.7 g $kg^{-1}$ | Plant nutrient | Zhang et al., 2011 |
| C: N ratio | High (56-266) | Potential for N immobilization | Solaiman et al., 2012 |

**Table SM3** (*Supplementary Material*)

| **Location** | **Soil type** | **Crop** | **Biochar rate** | **Yield increase** | **References** | **Remarks** |
|---|---|---|---|---|---|---|
| Brazil, tropical | Clay, Xanthic Ferralsol | Rice | secondary forest wood, 11 t $ha^{-1}$ | Doubled grain production | Steiner et al., 2007 | Only if fertilized with NPK |
| Columbia | Oxisol | Maize | 8 and 20 t $ha^{-1}$ | Progressive increase from 28 to 140% over 4 years | Major et al., 2010 | Liming effect, and increased availability of Ca and Mg |
| Western Kenya, bimodal rainfall | Light- and heavy-textured Ultisol | Maize | 6 t C $ha^{-1}$ | Up to 2.9 t $ha^{-1}$more than the control | Kimetu et al., 2008 | Reduced N immobilization due to reduced decomposition of biochar |
| Zambia | Various | Maize | Maize char up to 4t $ha^{-1}$ Charcoal dust up to 4 t $ha^{-1}$ | Between 80% and over 400% of the control | Cornelissen et al., 2013 | Variable |
| Norfolk, southeastern U.S. Coastal Plain | kaolinitic, thermic, typic kanditidult | | Up to 2% on a weight basis | | Novak et al., 2009 | Higher sorption capacity of biochar for selective nutrients (especially Ca, P, Zn and Mn). |
| Ghana | Sandy loam and silty loam | Maize | 3 t $ha^{-1}$ | 6% more root biomass production | Yeboah et al., 2009 | Up to 5% increase in N recovery |
| Indonesia | sandy loam | Maize | cattle dung and coconut shell, 15 t $ha^{-1}$ | Up to 5.9 t $ha^{-1}$ | Utomo et al., 2011 | Increased CEC, slower decomposition |

**Table SM4** (*Supplementary Material*)

| **Energy source** | **HHV (MJ kg$^{-1}$)** | **References** |
|---|---|---|
| *Pyrolysis products:* | | |
| Slow pyrolysis biochar | 28.7-29.3 | Woolf, 2008 |
| Fast pyrolysis biochar | 31.8-32.1 | Woolf, 2008 |
| Moderate pyrolysis biochar | 31.1-31.6 | Woolf, 2008 |
| Synthetic gas (syngas) | 11.1-12.8 | Bockelie et al., 2003 |
| Bio-oils | 17.0 | Laird, 2008 |
| Firewood or forest residues | 18.6 - 21.1 | Jenkins et al., 1998; Parikh et al., 2005; Woolf, 2008 |
| Crop residues | 15.8 - 20.5 | Parikh et al., 2005 |
| Charcoal: | 33 | Parikh et al., 2005 |
| Coal: | 24.0-31.0 | Parikh et al., 2005 |
| Coke | 32.4 | Parikh et al., 2005 |
| Cow dung | 6.3-13.4 | Sweeten et al., 2006 |