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Climate Change Impact Assessment of a Biochar System in Rural Kenya

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ABSTRACT

Biochar systems have been beneficial to Kenyan residents living in the rural areas, particularly in Kwale, following recent research interventions. Biochar system starts from the biomass feedstock sourcing, its production method, and finally its application to soil. The aim of this study is to assess the climate change impacts of the application of biochar in smallholder farms and households in rural Kenya, against the traditional agriculture and cooking practices under realistic conditions and from a life cycle perspective. The scope of this study includes the biomass sourcing identification, biomass availability measurement, cooking practice observation and biochar application during planting season (April to May) at one of the rural areas, the Waa Ward in Kwale County under The Biochar Project.

Field observation was carried out to identify and measure on-farm biomass availability and cooking performance. The identification and measurement of biomass weight were conducted through survey and manual scale, respectively. While the cooking performance was observed with uncontrolled Kitchen Performance Test (KPT) method. A life cycle assessment was conducted to evaluate the climate change impact of biochar system in Kwale. The biochar production method, also called the improved system in this study, is compared against the traditional system. This study focuses at the cookstove used for the two systems, Gastov and three-stone open fire. Gastov is a type of Top-Lit UpDraft (TLUD) natural draft gasifier cookstove investigated.

The biomass measurement established the biomass and energy availability on-farms in Kwale. Meanwhile, the KPT found that Gastov required lesser fuel for cooking due to higher thermal efficiency in comparison to three-stone open fire. The LCA results showed that the improved system performs better than the traditional system in terms of climate change impacts and that the improved system potentially offset GHG emissions caused by traditional system as well as generates a net carbon credit. Lastly, the ‘hotspot’ of the improved system was identified in the cooking process, although it was also significantly better than the traditional cooking process. The sensitivity analysis showed that both fraction of stable carbon and fraction of non-renewable biomass (fNRB) were major factors in the biochar system in Kwale, Kenya.

The conclusion is that the biochar system presents more advantages as applied in Kwale compared to the traditional system through biomass management, improved cooking method, and biochar application to soil.

Keywords: Biochar; biochar system; Life Cycle Assessment; climate change; three-stone open fire; TLUD gasifier; greenhouse gas emissions; climate change mitigation

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Abbreviations and Acronyms

3S	Three-stone open fire
BC	Black carbon
bc	Biochar
C	Carbon
Ca	Calsium
CEC	Cation exchange capacity
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
Cp	Specific heat capacity
EC	Energy consumption
ECTA	Europe Chemical Transport Association
ED	Energy delivered
EF	Emission factor
FC	Fuel consumption
fNRB	Fraction of non-renewable biomass
fRC	Fraction of recalcitrant carbon
fw	fuelwood
GDP	Gross domestic product
GHG	Greenhouse gas emissions
GJ	Giga joule
GoK	Government of Kenya
GWC	Global Warming Commitment
GWP	Global Warming Potential
H	Hydrogen content
ha	Hectare
HH	Household
HHV	Higher heating value
H_l	Latent heat of vaporisation
ICRAF	World Agrogorestry Centre
ICS	Improved cookstoves
IITA	International Institute of Tropical Agriculture
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardisation
K	Potassium
kg	kilo grams
kJ	kilo joule
KPT	Kitchen performance test
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower heating value
M	Moisture content
Mb	Total biomass
m_{fc}	mass of food cooked
Mg	Magnesium
MJ	Mega joule
MoE	Ministry of Energy (and Petroleum)
MRT	Mean residence time
N_2O	Nitrous oxide

NEMA	National Environment Management Authority
NMHCs	Non-methane hydrocarbons
NRB	Non-renewable biomass
O	Oxygen content
OC	Organic carbon
OECD	Organisation for Economic Co-operation and Development
pH	Potential of Hydrogen
PIC	Products of incomplete combustion
PJ	Peta joule
PM	Particulate matter
RB	Renewable biomass
RF	Radiative forcing
SO_2	Sulphur oxide
SOC	Soil organic carbon
SOM	Soil organic matter
TC	Total carbon content
TLUD	Top-lift updraft (gasifier)
TSP	Total suspended particles (in pollutant mass)
TSPC	Total suspended particles (in carbon mass)
UN	United Nations
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
WHC	Water holding capacity
WRI	World Resources Institute
Y	grain yield of maize
η	Overall thermal efficiency
ΔT	Temperature difference
°C	Degree of Celcius
F_d	Fuel consumption
C_{em}	Carbon emitted

Chapter 1: Introduction

Biochar application is getting significant attention as a climate change mitigation tool globally, in particular, less developed countries. In the current chapter, a background of the study and the aim of this study will be given, as well as delimitations and research gaps of this study. Lastly, the hypothesis of this study is presented at the end of this chapter.

1.1 Background of the Study

Development challenges in Kenya

Studies have identified that countries in Africa, including Kenya, are vulnerable to climate change and environmental degradation due to prevailing climatic conditions and its reliance on agriculture to economic growth (Serdeczny et al., 2017; Awuor et al., 2008; Bryan et al., 2013). In the study by Serdeczny et al. (2017) investigated that the country is experiencing increases in temperature, leading to increase in evapotransporation, resulting in crop failures, rises in land diseases and pests, degradation of soil quality, flooding of farmlands, and shifts in land use in terms of agro-ecological zonation. The other climate change impacts that the country is facing are floods and drought episodes caused by variations in general circulation patterns.

Over 80% of the population in rural Kenya directly or indirectly depends on agriculture for their household income (Kenya Agricultural Research Institute, 2012). Agriculture was reported to employ more than 60% of Kenyan's population, although it contributes with less than one third to national GDP of Kenya (World Bank, 2017). Considering informal employment and family labour, the significance of agriculture for Kenyan's livelihoods increases even further.

Energy is another sector that heavily relies on natural resources, further intensifying the above-mentioned dilemmas faced by the country. According to (Owiro et al., 2015) biomass energy accounted for 68% of all energy consumed in Kenya. For a long time, biomass energy was easily accessible in the vicinity, with plentiful natural forests freely supported the wood fuel (charcoal and firewood) basically for all domestic energy requirements (Otieno and Awange, 2006). Besides from the closed forests, biomass energy resources are derived from woodlands, bush lands, farm lands, plantations and agricultural and industrial residues. However, due to deforestation and depleting of other biomass sources, wood fuel has been a commodity that one needs to buy in the local markets (Kiplagat et al., 2011).

The rapidly growing population in Kenya increases the gap between the demand and the lack of sustainable supply of wood fuel (Owiro et al. 2015). Forests are destroyed much faster than they are regenerated (Otieno and Awange, 2006). In addition to provide the populations with fuel, deforestation has happened due to large conversions of these forests to agricultural land (Lal and Singh, 1998). And thus, resulting in soil degradation and a decrease in soil nutrient retention and supply (Kimetu et al., 2008). The attempts to solve these challenges, including to maintain the soil quality as well as providing biomass energy for rural households, should be the ultimate goal for Kenya in order to strengthen the economy, protect environment, improve quality of life, and accomplish greater equity. (Torres-Rojas et al., 2011; UN General Assembly, 2013)

Life Cycle Assessment

Life Cycle Assessment (LCA) has been recognised as one of the most important methods for assessing environmental impacts associated with a process or a product (Klöpffer and Grahl, 2014). There are multiple objectives of doing LCA as an environmental management tool, among them are: 1) to assess the environmental performance of a process or a product from cradle-to-grave, hence, helping stakeholders and decision-makers to select between alternative process or product; 2) and to offer a foundation for evaluating the potential environmental performance improvements of a process or a product (Azapagic, 1999). LCA has been standardised in ISO 14040 and 14044 for LCA (Figure 1.1), and thus, it is possible to adapt LCA approach to particular requirements of different research (Guinée, 2001).

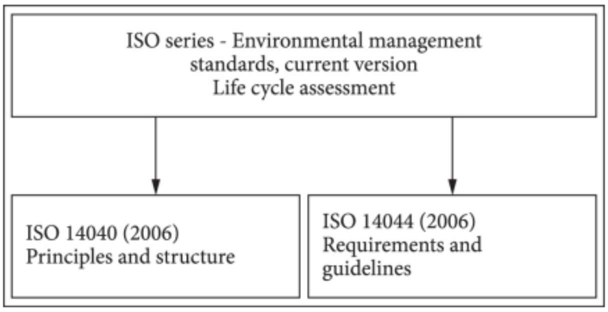

Figure 1. 1. *ISO standards for practicing LCA. Adapted from Nigri (2014)*

1.2 The Biochar Project in Kenya

The project "Biochar and smallholder farmers in Kenya" or referred as "The Biochar Project" in short, studies the role of biochar in smallholder farming systems in Kenya. The project is a collaboration between World Agroforestry Centre (ICRAF), International Institute for Tropical Agriculture (IITA) and the Wangari Maathai Institute (WMI) for Peace and Environmental Studies, University of Nairobi, in Kenya, KTH Royal Institute of Technology, Lund University, and Swedish University of Agricultural Sciences, in Sweden. The research was started to tackle the issues of soil fertility, fuel efficiency and exposure to indoor smoke, and thus four joint measures were suggested, as follows:

1. broadening the resource base by using farm-level organic resources;
2. combining cooking and heating with the production of charred biomass;
3. using charred organic matter as a soil amendment in agriculture; and
4. improving and applying more efficient stove technology for cooking and char production.

The terminology of charred biomass is divided into two, charcoal and biochar. Biochar is the term where charred biomass is applied to soil in order to improve soil properties, while charcoal is where charred biomass is used as fuel (Lehmann and Joseph, 2015). Combustion, gasification, and pyrolysis are the most common thermochemical conversion routes for recovering energy from biomass. Biomass carbonisation is a thermochemical conversion of biomass materials into char (Antal and Grønli, 2003). On the other hand, biomass gasification is the conversion of biomass feedstock into convenient gaseous fuel (energy) and production of char at the same time (Basu, 2013).

The Biochar Project selected a TLUD gasifier to fit in the demand of the farms of producing biochar, after pre-tests at the University of Nairobi (Sieber, 2016, p. 24), the Top-Lit UpDraft (TLUD) gasifier cook stove produced by Kenya Industrial Research and Development Institute (KIRDI), known as Gastov. The Gastov consists of several parts including a removable fuel canister, a ceramic insulated body that insulated heat, a burner, and a pot skirt (Figure 1.2). The Gastov was developed for different type of biomass fuel, including firewood, pellets, charcoal briquettes, and crop residues (e.g. maize cobs and coconut shells) and the fuel loading is done in batch.

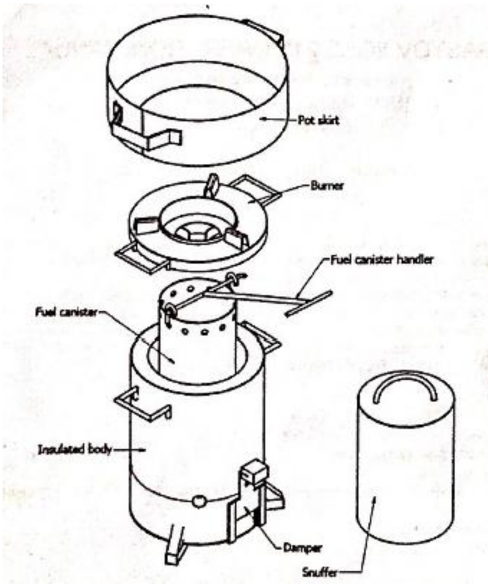

Figure 1. 2. *The Gastov parts. Adopted from KIRDI (2016)*

This study continued from previous work under this project by Sieber (2016). This study, however, only focused on one area under The Biochar Project, namely Kwale, instead of investigating the biochar system in the country. Another development accomplished in this study was by using 'realistic household conditions'. The 'realistic household conditions' was defined as a condition of non-controlled household environment during the field observation period, and is furthered discussed in Chapter 3.

The research gap that is addressed on this study was identified from the previous LCA study on biochar application in the Biochar Project by Sieber (2016). Sieber (2016) mainly used literature or secondary sources for quantifying biomass feedstock to the cooking system. Given the locally available feedstocks and biomass sourcing practice, further research was needed regarding quantifying locally available biomass. One contribution of this study is to close the research gap is by conducting a biomass measurement at household level. The data from this measurement is used for life cycle assessment, in order to obtain results under 'realistic' conditions.

1.3 Research Aim and Objectives

The aim of this study is to assess the climate change impacts of the biochar systems in smallholder farms in rural Kenya, against the traditional agriculture and cooking practices from a life cycle perspective.

The objectives of this study are:

- To obtain the data required for the assessment during field study in Kwale, Kenya. The data includes biomass feedstock, fuel efficiency of both traditional and 'clean' cookstove, and plant yield.
- To assess and compare the climate impacts of biochar production and application, as a soil amendment, against the traditional practices in Kwale, Kenya, using LCA.

1.4 Delimitations

As mentioned previously, The Biochar Project was established for a smallholder farming system, and thus, this study follows people-centred development approach at the household level. The smallholder farming system takes numerous factors into consideration, including:

- traditional local practices;
- personal preferences;
- organic resources available at farm level;
- household energy needs for cooking;
- stove performance under practical use in each household; and
- local soil conditions and farm management

This study is conducted at model farms in Waa Ward, Kwale, and will be further discussed under Chapter 3.

1.5 Layout of the Report

This report is divided into six chapters. Chapter 1; gives the introduction and presents the aim and objectives of this study. This chapter also describes the delimitations of this study.

Chapter 2 contains literature review of field observation related aspects and LCA on biochar. The first half of the chapter relates to the field observation consists of the general conditions and current practices in rural Kenya. The second half reviews the climate change impacts of biochar system assessed using LCA.

Chapter 3 covers a walk-through of the research technical framework and methodologies used in this study. The methodologies include the methodology performed in the field, including biomass measurement and Kitchen Performance Test (KPT), and technical framework of LCA.

Chapter 4 presents the results both from field observation and LCA. A short analysis of the results is also included in this chapter.

Chapter 5 discusses both results from field observation and LCA. The discussions are based on the previous findings and relevant literature.

Finally, in Chapter 6, the conclusions are stated. In addition, the recommendations of future research direction are also written in this chapter.

Chapter 2: Literature review

This chapter reviews scientific literature regarding biochar production and application. The first half of this chapter reviews conditions in Kenya related to biochar study, while the last half reviews the life cycle assessments performed on biochar study.

2.1 Smallholder farms in Kenya

This section covers current practices and challenges as well as improvements that have been implemented in Kenya regarding the cooking energy and agricultural sectors.

2.1.1. Current Practice and Challenges in Kenya

Energy supply and demand

Kenya is considered to be a low forest cover country as it has less than 10% of its total land area categorised as forest. Data from early 2000s shows that Kenya's forests cover less than 2% of the country's landmass and divided into natural (2 million hectares) and plantation forests (approximately 0.24 million hectare) (JICA, 2002 cited in National Environment Management Authority, 2009). Persisted losses of forests and related resources have had significant negative impacts on the country's economy and welfare. Some effects include insufficient supply of fuelwood and timber which cause overexploitation of trees, eventually leading to environmental degradation and biodiversity loss among others (Nellie and Githiomi, 2009 cited in Githiomi, 2012).

Mostly in developing countries, lack of access to clean and reliable energy sources and their affordability results into the uncontrolled used of solid fuels (Othieno and Awange, 2016). The average Kenyan household, which consists of 4.4 people, was still almost depending entirely on firewood, bio-waste and charcoal for energy, despite a contrast between rural and urban areas as well as lower and higher income groups exist (Munene, 2004). Nationwide percentage of 68.3% and 13.3% of the country's household population used firewood and charcoal for cooking, respectively (NEMA, 2009). With more than 80% of households in the rural areas used firewood for cooking (NEMA, 2009). By improving the efficiency of biomass combustion, biomass can be a key role in the future of the country's energy system, as it is locally available and possibly renewable.

Household cooking practice in rural Kenya

Hall and Scrase (2005) reported that 100% of households in rural areas in Kenya used fuelwood for cooking while maize cobs were used during harvesting season in addition to the fuelwood. There was a significant difference of fuelwood used in rural areas with fuel sufficiency and those where wood fuel was scarcer. Where fuelwood was abundant, farmers barely used any other fuel, and would keep the fire burning even after not needed for cooking. Where fuelwood was scarce, wood still provided energy needed for the majority, but it was bought at the market. Other types of fuel namely animal manure and crop residues were also used for cooking.

Torres et al. (2011) conducted a study of biomass availability for energy consumption on household level in Western Kenya. The study specifically measured availability of on-farm biomass for cooking purposes. It was found that the total annual fuelwood energy available in the farms of 5.3 GJ per capita could not fulfil the current cooking energy needs using conventional cooking method, but may be adequate for improved cookstove depending on their energy efficiency.

Traditional three-stone open fire has been known as the most commonly used cooking method in rural Kenya (Loo et al., 2016). Use of biomass fuels on three-stone open fire method has been associated with a significant amount of biomass fuelwood use, complicated mixture of indoor air pollutants including carbon monoxide (CO), particulate matter (PM) and atmospheric pollutants such as black carbon (BC) and higher emissions of products of incomplete combustion (PICs) (Wilkinson et al., 2009; Ochieng et al., 2013). PICs such as CO, methane (CH_4), and PM, which have greater impacts on climate than carbon dioxide (CO_2) (MacCarty et al., 2008). Particulate BC to have a global warming effect and has been estimated to be the second largest global warming agent after CO_2 (Bond et al., 2013). Although the uncertainties of particulate carbon emitted from the household sector is high, however, it has been estimated that 39% of particulate carbon emitted from power and industrial biofuel combustion contributes to total global combustion particulate emissions (Bond et al., 2004b).

The daily PM intake from cooking activity is more directly related to health risks of the person cooking (Grieshop et al., 2011). BC has been associated with damaging effects on human health (Jerrett et al., 2009). The health risk associated with indoor air pollution from traditional cooking and heating practices are deleterious respiratory effects that are felt by women and children whom typically spend more time in the kitchen (OECD/EIA, 2014, p. 30). A study conducted in Kwale county in Kenya by Majdan et al. (2015), found that over half of the participants of the study suffered a respiratory sickness once or twice a year and over one third discovered such problems up to five times a year. Another study conducted in the same county by Gitau et al (in press) found that most of the women who collected the firewood complained of long-term physical burden.

Agricultural practice and soil condition

Kenya has a remarkably diverse physical environment, including tropical rainforest, savanna grasslands and woodlands, and semi-desert environment. Despite the diverse physical environment, agriculture plays a major role in Kenya's economy. The agricultural sector in Kenya consists of a total six sub-sectors including industrial crops, food crops, horticulture, livestock, fisheries and forestry. In terms of production scale, agriculture sector is divided into three, small-, medium-, and large-scale farming. In small-scale farming, 0.2 to 3 acres, farmers mainly produce crops for own-consumption rather than selling off to the local market. (Government of Kenya, 2010) Maize, potato, cassava, vegetables, and beans are the most common species of food crops grown in this system, with maize crops accounting for over 50% of the crop area and the calories consumed in the country (Smale et al., 2013).

Soil properties also has a great diversity in Kenya, just like the country's physical environment. There is a similarity found in this diversity, a lack of major nutrients essential for soil including nitrogen, phosphorous and potassium. Arid and semi-arid lands, which comprises about 84% of the country, are characterised by shallow and less developed soils with low content of organic matter (Kabubo-Mariara and Karanja, 2007; Government of Kenya, 2010). The major problems in small-scale farms are low soil fertility, disease, and nutrition, and thus, increasing productivity was often unsucessful (Government of Kenya, 2010; Sanginga and Woomer, 2009). The soils quality, on which small-scale farmers heavily depend on, have been exposed to erosion and loss of organic matter (Stocking, 2003). Despite the continuous cultivation of maize, the average grain yield of maize in the country did not sustain with the consumption (Wheeler and Von Braun, 2013). Instead the continuous cultivation, which mines soil organic matter and nutrients, in addition to decline in intercropping and insufficient use of rotations with other crops, has also contributed to decline in soil fertility. These signs of degradation could add risk to food security and ecosystem quality (Bai et al., 2008).

The current management practice of on-farm organic wastes and resources shows a significant loss of carbon and eventually mineral nutrients in the soil. Strobel (1987) observed that the readily available principal sources of organic farm inputs in Kenya are maize stover, comprising of the dried leaves and stalks of maize crops, and livestock manure, primarily from cattle raised in the farms. If it does not serve as farm inputs, the organic resources are usually found to be openly burnt or left for natural decomposition on the field. Otherwise, if the organic resources are not used for both mentioned purposes, they are used as a feedstock for traditional household cookstoves (Lehmann and Joseph, 2015; Lehmann et al., 2006). Due to bad practice, it has been found that organic carbon content in some parts of Kenya have declined after long term of continuous maize cropping, it reflects an imbalance between organic inputs and losses from soil (Lehmann et al., 2006; Woomer et al., 1998; Giller et al., 2011).

Climate change

In Kenya, climate sensitive natural resources are the country's social and economic pillars such as agriculture, forestry, tourism, and hydro-energy sectors (Mutai et al., 2011). Despite its insignificant contribution to global GHG emission, Kenya has been suffering from extreme climate events: extreme flooding; prolonged droughts; frost in some of the productive agricultural areas; increasing lake level; among others causing economic losses and negatively affecting food security (Government of Kenya, 2013, p.4). Over decades, El Nino Southern Oscillation has been identified to cause periods of drought and flooding in Kenya (Government of Kenya, 2016).

While it is the backbone of the country's economy, the agricultural sector has been the biggest contributor of GHG emission in the country (Climate Watch, 2018). Therefore, mitigation strategies can significantly lessen vulnerability to climate change by giving communities live in the rural areas a better ability to adjust to climate change and variability and cope with adverse consequences (IPCC, 2014a). At the farm level, measures include alterations in crop management practices, livestock management practices, land use and land management, and livelihood strategies (Ali and Erenstein, 2017).

Energy is also an essential aspect of climate change, as it is the second largest contributor to climate forcing emissions (Climate Watch, 2018). The energy-use patterns among household in Kenya drew a significant attention, due to the heavily dependent on solid biomass for basic cooking and heating (Kituyi et al., 2001). At the household level, combustion of solid fuels produces pollution that is damaging to health and environment as it releases large amounts of BC and carbon-based GHGs (Ezzati and Kammen, 2001; Bond et al., 2004a). In perfect combustion, emissions from burning solid fuel would only be CO_2 and water (MacCarty et al., 2008). However, as previously mentioned, many of the traditional cooking practice fell into incomplete combustion, which are more damaging in terms of global warming potential than carbon dioxide released from fossil fuel-burning stove (Smith et al., 2000). Especially, if such biomass fuels were harvested non-renewably (MacCarty et al., 2008).

2.1.2. Improving Health and Energy Security in Kenya

After discussing the major challenges in Kenya, from household level to the national level, this section discusses multiple solutions to tackle the abovementioned challenges. This chapter also discusses the reason behind improved cookstoves (ICS) being the centre of the solution.

Improved Biomass Cooking Method

Negative environmental and health problems associated with traditional cookstove and indoor air pollution in the kitchen could be addressed through cleaner, higher efficiency, biomass cooking methods. Due to the emission factors from biomass cookstoves are calculated per mass of fuelwood burned (Coffey et al., 2017), cleaner biomass cookstoves that reduce fuel consumption could potentially mitigate the health and climate change impacts of biomass burning in traditional cookstoves (Njenga et al., 2016). ICS offer a potential solution by having properties of increased thermal efficiency and reduced emissions (Grieshop et al., 2011). Increasing thermal efficiency will lessen fuel need for a cooking activity in overall, although not inevitably lessen PICs emissions (Grieshop et al., 2011). If combustion efficiency is improved at the expense of heat transfer efficiency, emissions per activity can be reduced (Grieshop et al., 2011). By reducing methane, of the PIC emissions, and BC, near-term climate change may be reduced, since methane and BC are short-lived relative to the long-lived GHGs (e.g., CO_2) (Jackson, 2009). In addition, controlling methane and BC emissions may considerably help improving health aspect (Ramanathan and Carmichael, 2008).

ICS started to be developed in 1970s, nearly five decades ago, and until the new millennium the design were primarily focused on increasing fuel efficiency, often due to the understood relationship between household energy and deforestation (Arnold et al., 2003 in Ruiz-Mercado et al., 2011). Efforts to improve health by reducing air pollution as well as to mitigate climate change impacts of cookstoves have started to be included in the design considerations more recently (Smith and Haigler, 2008). An analysis study by Smith and Haigler (2008) also showed that ICS are effective in improving health and reducing positive climate forcing. ICS have been developed with different designs and materials, from mud stoves to metal stoves. Table 2.1. lists down the average efficiencies of traditional stove, three-stone open fire, and ICS categorised by the biomass fuel type used. For the past decades, a lot of effort has been dedicated to develop ICS, which improves thermal efficiency by 10-25% (Table 2.2) and reduce fuel use by 30-40% with equivalent reduction in associated emission, in comparing to the traditional stoves (Garrett et al., 2010). Biomass gasifier, charcoal and fan-assisted cookstoves have been proven to be superior to traditional stoves (UNEP, 2011).

Biomass micro-gasification cookstove, where biomass fuel is converted to a clean synthesis gas that is burnt, and a solid charcoal residue is produced, has been developed as one of the key alternatives for ICS design (Roth et al., 2014). The central element of the Biochar Project is a gasifier cookstove for households which combines providing energy for cooking and producing char. In gasification process, two stages of combustion, gas generation and oxidation, often overlap and take place at the same time (Roth et al., 2014; Basu, 2013). By keeping the primary air from entering the hot char-bed at the end of conversion phase, char gasification can be repressed, and char can be produced and stored for other use later (Basu, 2013). Recovering heat from char production is an alternative to increase the overall fuel efficiency (Roth et al., 2014).

Table 2. 1. *Cookstove types used in developing areas categorised by their fuel (Boulkaid, 2015; Kaygusuz, 2011)*

Type of Fuel	Type of Cookstove	Thermal efficiency (%)
Firewood	Three-stone open fire	10-15[a]
	Brick stove	13-16[b]
	Metal stove	20-30[b]
	Rocket stove	30-35[a]
	Gasifier	25-35[c]
Charcoal	Mud stove	15-25[b]
	Traditional Jiko	20-25[a]
	Kenya Ceramic Jiko	25-30[a]
	Gasifier	30-35[a]
Crop residues	Three-stone open fire	10-15[a]
	Gasifier	30-35[a]

Source:
[a] *Boulkaid, 2015*
[b] *Kaygusuz, 2011*
[c] *Panwar, 2009*

Most gasifier stove models follow the basic Top-Lit Up-Draft (TLUD) principles (Figure 2.1). Using this stove, the fuel is loaded all at once into a container and lit from the top of the stove. A performance review of TLUD gasifier cookstove by Roth et al. (2014) showed the major benefit of using it in comparison to three-stone open fire. The performance indicator used were emissions of CO and PM. The study found that if charcoal produced is not burnt, emissions are lower. However, comparing the fuel consumption of TLUD gasifier stoves with three-stone open fire was found to be complex due to batch-loaded fuel specification of the stove. With three-stone open fire, additional feedstock can be inserted into the fire continuously and easily, as with TLUD gasifier, it is more difficult to accomplish in the case of an enclosed stove design (Roth et al., 2014). In Kenya, however, the main challenge was to develop a gasifier that is easy to use, affordable, as well as portable enough so the cooks can move it if necessary including lighting it from outside to reduce indoor air pollution (Njenga et al., 2016).

One of the strength of cooking with a gasifier is the use of a broad variety of solid biomass including residues that can otherwise not be completely and cleanly burned in another ICS (Roth et al., 2014). Therefore, farm-level organic resources and crop residues including maize stovers, maize cobs, coconut shells, coffee husks, and small pieces of tree pruning/branches can replace fuelwood collected from forests. Crop residues open burning is the most common practice found in less-developed countries, including Kenya, which causes GHG emissions, in particular CH_4 and N_2O (Akagi et al., 2011). Using crop residues as an alternative to fuelwood has a large GHG mitigation potential, while also increasing energy access for low-income, rural communities (Vitali et al., 2013).

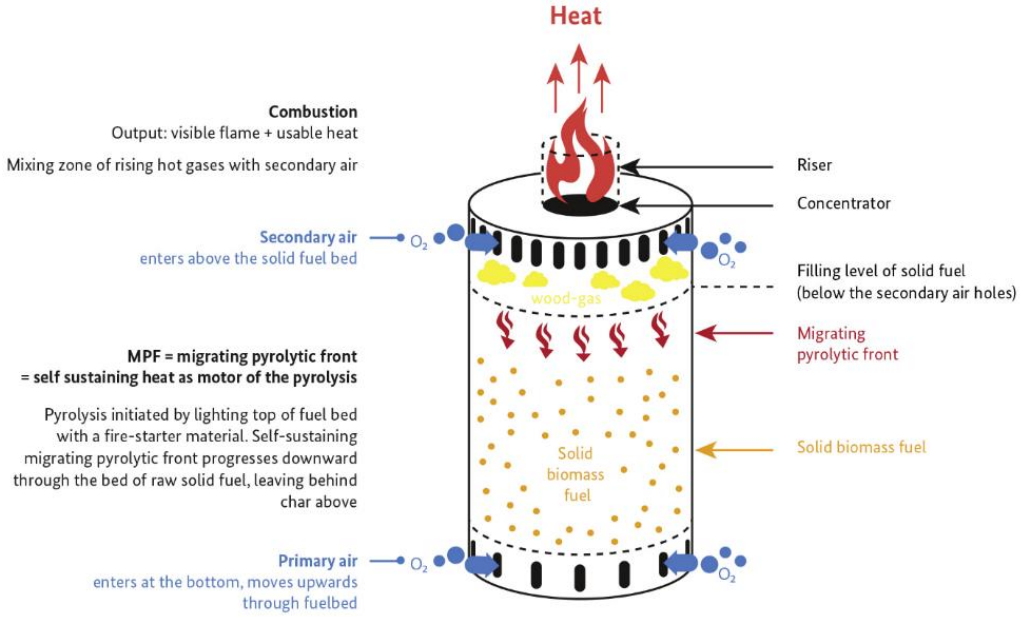

Figure 2. 1. *Working principle of TLUD gasifier (Roth 2014, p. 23)*

Biochar production

In addition to cooking and heating, gasifier stoves can also be used to produce char, which is also the purpose of the Biochar Project. The char product can be used again as 'charcoal' for cooking and heating or as 'biochar' for improving soil properties and storing long-term carbon. The method in which can be produced in TLUD gasifier cookstove is by removing the char before it combusts and turns to ash (Roth et al., 2014).

Lehmann (2015, p. 2) distinguished the biochar from charcoal that is used as fuel for heat by defining biochar as the proper term where charred organic matter is applied to soil, with intention to improve soil properties. A more technical definition of biochar is defined by Shackley et al. (2010, p. 9): "porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen depleted atmosphere which has physiochemical properties suitable for the safe long-term storage of carbon in the environment and, potentially, soil improvement".

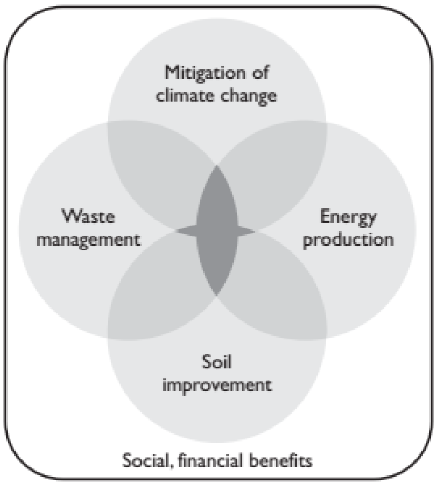

Figure 2. 2. *Motivation for applying biochar technology (Lehmann and Joseph, 2015, p.5)*

The processes to produce biochar occur in gasifier stoves. As discussed in the previous section, a gasifier stove consists of two processes (See Figure 2.1). First, solid biomass fuel is pyrolised into a mixture of hydrocarbon-containing gases and charcoal. Pyrolysis is a thermo-chemical decomposition in the absence of oxygen. Second, the gasses are burnt with a smokeless flame. During this time, the operation of stove is discontinued when the flame goes off and the char is removed as a product. In contrast with pyrolysis, char gasification requires a medium like air or oxygen to convert the solid biomass feedstock into gasses or liquids. (Carter and Shackley, 2011; Basu, 2013)

Lehmann and Joseph (2015, p.5) classified four complementary objectives may encourage the application of biochar including soil improvement (improved productivity and reduced pollution); waste management; climate change mitigation; and energy production (Figure 2.2.). Biochar production provides an opportunity to improve soil fertility and nutrient-use efficiency by using biomass feedstock in a sustainable way (Lehmann and Joseph, 2015; Basu, 2013). Adoption of biochar technology does not involve new sources, instead using existing resources in more efficient way. Small-holder farmers are able to use crop residues and biomass fuels without compromising energy yield. By improving soil, food security problems in the country can be solved (Stavi and Lal, 2013). Further discussions on biochar system and application are discussed in the next section.

2.2 Climate change impacts of Biochar system

In this section, different biochar systems from different areas are comprehensively reviewed. The reviews focus on the climate change impacts from biochar production and biochar application.

2.2.1 Climate change impacts of producing and using biochar

In 2014, Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014b) reported that "global emissions of greenhouse gases have risen to unprecedented levels despite a growing number of policies to reduce climate change". GHG emissions have to be lowered by 40-70% by mid-century in comparison with levels of 2010, and to near-zero by the end of the century, in addition the increase in global mean temperature has also to be limited by 2ºC (IPCC, 2014b). Stabilising GHG concentrations in the atmosphere involves emission reductions from energy production and use and other sectors. Using energy efficiently is as important as cutting emissions from electricity production. A lot mitigation measures can contribute to sustainable development by providing energy access and reducing local air pollution (IPCC, 2014b). In this case, biochar system, starting from feedstock sourcing, biochar production, to soil application, is an excellent climate mitigation measure (Whitman et al., 2010).

Within a biochar system, emission reductions could come from every phase, including from converting fresh organic matter to a more stable form of carbon through biochar production, from rising soil carbon stocks through biochar application, reductions in GHG soil emissions, improved carbon storage in growing crops and less use in fertiliser and other energy-intensive agricultural inputs (Roberts et al., 2009; Whitman et al., 2010). In biochar cook-stove system, emission reductions would derive from higher stove efficiencies, leading to less amount of total biomass feedstock for fuel use and cleaner cooking heat production, resulting in lower GHG emissions per unit of fuel used (Whitman et al., 2010). When applying biochar to soil, the carbon can be sequestered in the soil for a long period of time, hence, carbon that is normally released as CO_2 from biomass degradation is prevented (Wang et al., 2013).

2.2.2 Biochar cookstove system

Capturing energy during biochar production and using the biochar converted during pyrolysis process as a soil amendment are equally valuable for reducing biomass feedstock as well as reducing indirect emissions (Lehmann and Joseph, 2015). In most of rural Africa, including rural regions in Kenya, pyrolysis for bioenergy production offers a more efficient energy production than traditional wood burning cooking method (Ochieng et al., 2013). Biochar cookstove system also expand the options of biomass feedstock used for generating energy, from wood to crop residues. If the biochar cookstoves are more efficient and cleaner burning than traditional cookstoves, they could considerably diminish fuel collection pressure and respiratory diseases that is caused by indoor pollution by smoke generated during the biomass burning (Jeuland and Pattanayak, 2012).

Sparrevik et al. (2013) evaluated different biochar productions (earth-mound kiln, improved retort kiln, and TLUD gasifier) in Zambia. The effect of PM formation in all three biochar productions used in the study was lower without biochar application to soil. The use of TLUD gasifier for cooking replacing three-stone open fire in closed spaces results into more positive health effects than other biochar production method used in this study. In this area, using TLUD gasifier for cooking also found to reduce the need for firewood that leads to positive reduction of deforestation. In the end of the study, it was concluded that the optimal solution for biochar production and use depends on local conditions.

Biochar production systems in tropical rural areas was evaluated using LCA by Smebye et al. (2017). The study focused on the various pyrolysis methods suitable for rural tropical conditions, such as flame curtain kilns, earth mound kilns, retort kilns and pyrolytic cookstoves. It was found that pyrolytic cookstoves and gasifiers have the most positive environmental impacts due to avoided firewood consumption and emissions. Earth mound kilns showed to have the highest environmental impact due to a high release of both pyrolysis gases and PM. In regards to PM emissions impact, pyrolytic cookstoves performed best due to significantly low PM_{10} released. The study also included the material used for making the cookstoves, however, it was discovered that the material does not have significant contribution to life-cycle impacts as the long-life expectancy of the pyrolytic cookstove was assumed.

Whitman et al. (2011) studied the impacts of climate change of biochar cookstoves in farm households level in Western Kenya by using system dynamics modelling. The study compared the climate change impact between conventional cookstoves and ICS models available in the farm to produce biochar. The reduction in mean GHG impact from a pyrolysis stoves is up to

1.5 times compared to three-stone open fire, of which biochar directly accounts for 26-42% The reductions in gaseous emission in pyrolysis stove made up a big part of the reductions, though biochar production and rises in SOC both make significant contributions. The fraction of non-renewable biomass (fNRB) of off-farm wood and the basic amount for fuelwood demand was found to contribute the greatest impact on emission reductions since it alters both which GHG emissions are counted and whether biochar production is counted as C sequestration or as no net change in terrestrial C stocks.

In a study by Gaunt and Lehmann (2008) discovered that when biochar is added to soil instead of using it as an energy fuel, indeed, reduce the energy efficiency of pyrolysis process; nevertheless, the emission reductions associated with biochar application to soil found to be 2 to 5 times greater than the used solely for fossil energy offset. The feedstocks used in this study were corn stover and winter wheat straw. More than half of the emission reductions found are related to carbon retention in biochar, and the rests are offsetting fossil fuel use for energy, fertiliser input reduction, and avoided soil emissions other than CO_2.

Regardless the type of ICS used for producing biochar, it may increase efficiency of the ICS which leads to decrease in fuel consumption. The attempts to justify reduction in deforestations may be invalid if the wood left ungathered as a result of stove introduction is simply made available for another use (Whitman and Lehmann, 2009). Therefore, the production of biochar and its application to soils should be combined in a system, due to certainty of its sequestration, despite the effects of reduced fuel wood consumption (Whitman and Lehmann, 2009; Whitman et al., 2010).

2.2.3 Biochar application to soil

Biochar properties are greatly varied depending on the type of feedstock and pyrolysis process and conditions. Biochar produced at high temperature leads to a material similar to activated carbon, while low temperature may be appropriate to control fertiliser nutrient release (Amonette and Joseph, 2009). Carbon in biochar is extremely recalcitrant in soils because of the high aromaticity contained in biochar and usually longer than the residence times of most soil organic matter (SOM) (Chan and Xu, 2009). Hence, biochar applied to soil signifies a potential terrestrial carbon sink as well as mitigating CO_2 emissions (Lehmann et al., 2006). Cation exchange capacity (CEC) of soil increases when biochar is incorporated to soils and has been reported increased as the biochar ages. CEC is a measure of the surface charge in soil or biochar (Chan and Xu, 2009). The high porosity of biochar allows it to retain more moisture.

The effects of biochar amendment on soil vary greatly with soil and biochar types. For example, a series of experiments to identify the effect of biochar produced from woody and herbaceous feedstocks and applied to different type of soils in the Pacific Northwest of the United States was done by Streubel et al. (2011). The experiment highlighted different effects of different biochar to different type of soils based on soil properties such as soil pH, WHC, soil nitrogen mineralisation, soil carbon, carbon mineralisation. The study discovered that biochar feedstock is not an important factor in increasing pH or carbon in the local type of soils. The type of soils in the study was Quincy sand, Naff silt loam, Palouse silt loam, Thatuna silt loam, and Hale silt loam. Soil pH raised with biochar amendments on all soil types and biochar feedstocks. The use of biochar to increase pH may be advantageous where soils become acidic due to long-term fertiliser application. Soil WHC differed depending on rates of application and biochar feedstock. The biochar recalcitrant nature may also increase C sequestration in agricultural soils due to proportion of total C in biochar that is recalcitrant results in long mean residence time. The study concluded that biochar amendment is potential to improve humid temperate soils by adding carbon, increasing pH, and raising WHC.

Biochar is an ideal soil conditioner for tropical clay and sandy oils in Kenya due its properties such as high surface area and cation exchange capacity (CEC), high carbon content, high stability and nutrient content, low bulk density, and neutral to alkaline pH (Gwenzi et al., 2015). Pyrolysis temperature greatly impact the characteristics of biochar. A study by Wang et al. (2015) highlighted different characteristics of maize biochar produced at different pyrolysis temperatures and its effect on organic carbon, nitrogen, and enzymatic activities after incorporation to fluvo-aquic soil in North China. The pyrolysis temperatures used to produce biochar in the study were 300, 450 and 600 ºC. When the temperature was increased, ash content, pH, surface area, pore volume and aromatic carbon content of biochar also increased.

The application of biochar leads to soil quality enhancement which leads to improved seed emergence, crop growth and productivity (Gwenzi et al., 2015). In small-holder farms in Kenya, often found low crop yields due to low soil fertility, limited access to fertiliser, and limited moisture due to dry season and droughts. Using biochar as soil amendment can help mitigate this issue (Rockström et al., 2009). Some studies found yield increases after biochar application. Kimetu et al. (2008) studied the application of biochar to reverse soil productivity decline in Western Kenya. The study found that applying highly recalcitrant biochar at the most degraded areas (80-105 years since forest clearing) increased the maize crop yields by 2 magnitude. Adding biochar was shown to also increase soil properties such as soil pH, CEC, and soil organic carbon. Recalcitrant biochar has significant long-term benefits through their contributions to soil organic matter (Rillig and Thies, 2012). In this study, it was investigated that incorporation of biochar increased soil organic carbon by 45%.

A single biochar incorporation to infertile, acidic tropical soils improved maize and soybean crop yields up to at least four years after application shown by Julie et al. (2010) as another example of biochar amendment to increase crop yield. The study highlighted that a single biochar incorporation to soil may offer benefits over several cropping seasons, although a longer study is required to verify when a steady-state is achieved and when deterioration starts to appear. Crop yields after incorporating wood biochar in a Colombian savanna oxisol soil showed up to 140% greater yield. Yield improvement in the study was credited mainly to pH increase and nutrient retention.

The application of biochar in small-holder farms in Kenya also means to sequester soil carbon and reduce GHG emissions (Scholz et al., 2014). In addition to enhance soil quality and productivity, biochar has both direct and indirect impacts on GHGs. The direct impacts such as the stabilisation and sequestration of carbon in the soils. The impacts of biochar incorporation also shown on non-CO_2 GHG emissions. Higher GHG emissions on tropical soils than in temperate soils could be stimulated by extremely seasonal wet and dry cycles also fluctuating temperatures. A field experiment to investigate the effect of biochar on maize yield and GHGs in a calcareous loamy soil poor in organic carbon in China was done by Zhang et al. (2012). The study focused on the soil emissions of CO_2, CH_4, and N_2O to determine the effect of biochar incorporation effect on GHGs. Maize yield was found to increase by up to 12% with N fertilisation and up to 15% without N fertilisation. Total global warming potential (GWP) decreased when biochar was applied to the soil of up to 47% with and without N fertilisation. Although the soil CO_2 emission increased without N fertilisation. Biochar application was also found to reduce soil bulk density and increase soil total N contents, although no effect on soil mineral N. The study concluded that incorporating biochar as soil amendment to calcareous and infertile dry croplands poor in soil organic carbon may improve crop productivity and reduce GHG emissions.

Lastly, soil responses to biochar incorporations are the net results of production (e.g. feedstock and pyrolysis productions) and post-productions (storage) conditions. These conditions can result to significantly unique properties to each batch of biochar, even when produced from the same feedstock and pyrolysis unit (Spokas et al., 2012). Soil responses to biochar application are also different on each type of soils and climates (Lehmann and Joseph, 2015).

Chapter 3: Research Framework and Methodology

This section presents the research framework and methodologies used in this study, from data collection to the assessment method, and is divided into three sub-chapters. Chapter 3.1 describes the methodology for conducting field trip, includes kitchen performance test (KPT) and biomass survey. Chapter 3.2 describes the theoretical framework of selected assessment method, Life Cycle Assessment (LCA). Lastly, Chapter 3.3 describes the system and the inventory of LCA.

3.1 Field Data – Collection and Analysis

This section explains the method of the primary data collection required for Life Cycle Inventory (LCI), further explained in Chapter 3.2.2, that was conducted during the long-rain and planting season, April 2018 – May 2018.

3.1.1 Study area

The study was carried out in Waa Ward (Kwale County), a coastal region of Kenya, about 515 km from Nairobi. With an estimation of 890,314 people lived in Kwale in 2014 and around 80% of the region's economy was contributed from agriculture activities. The area is covered with sandy deposits, shale and limestone type of soils. In addition to cultivation of maize crops, farming of coconut and cashew nut are the main cash crop production activities in Kwale. The traditional three-stone open fire is the most commonly used cooking technique and fuelwood is the primary source of cooking energy (Gitau et al., forthcoming). The improved cook stove in this study was The Gastov, a TLUD gasifier cookstove selected by The Biochar Project.

3.1.2 Farm selection

The twelve household farms participated in this study were randomly selected from a sample of 50 farmers included in The Biochar Project using 'Random' function in Excel. All farmers selected through random sampling were willing to participate in this study.

Figure 3. 1. *Libbis Sujessy, James Gitau and a farmer weighing tree prunings using a spring balance*

3.1.3 Biomass measurement

Household data and data on farm production and biomass use were collected through observation and survey questionnaire for farmers (Appendix A). Figure 3.1. shows a picture that was taken during the observation of how the wet woody biomass obtained from pruning branches was weighted. Each selected farm was surveyed to identify farm and biomass sources for potential use as cooking fuel. Data collected included type of crops grown, area of crops grown, and age of crops grown.

Since the field study was performed during planting season, only woody biomass was used for cooking. The identification of fuel for cooking was done with structured questionnaire, while the identification of species of trees was classified by talking with the farmers on their respective farms. Based on the questionnaire, biomass measurement in this study was accomplished solely for pruned woody biomass. The questionnaire used to identify the biomass management in household farm level is shown in Figure A.1. In addition to the identification, the physical counting based on age categories of the trees were done with the help of the farmers to reach more accurate approximation of available pruned biomass (Appendix A).

The weight of freshly pruned wood was measured with a scale. The same biomass measuring method, specifically for pruned biomass, has been applied by Bilandzija et al. (2012) for identifying energy potential of pruned biomass in Croatia. Based on the pruned biomass calculations, the biomass energy availability for cooking was calculated for each farm. It was assumed that the biomass sources did not have competing uses within the farm, based on the results of biomass survey. This led to a result where the total available pruned biomass on the farm was entirely used for cooking purpose. To determine the energy available for pyrolysis cooking in the farm, a study by Torres et al. (2011) suggested the calculation by multiplying the total available biomass with the heating value of the respective type of biomass. The following Equation (3.1) was applied:

$$E_c = M_b \times LHV \tag{3.1}$$

where E_c is the energy available for cooking (MJ), M_b is the total pruned woody biomass (kg) and LHV is the low heating value energy content of the feedstocks (MJ/kg). The value of estimated LHV for each type of woody biomass is presented in Appendix B.1.

3.1.4 Kitchen performance test (KPT)

KPT was conducted to determine the energy consumption per capita per meal that also serves as a functional unit in the LCA study. Four out of twelve farms did a kitchen performance test (KPT), cooking the same type of dishes using the two cooking techniques, traditional and improved stoves. Fuelwood, biomass, char residues, and biochar were measured during daily cooking activities per household. The observations during KPT were assisted by a PhD researcher from University of Nairobi and a local guide in order to ensure that the observations ran smoothly. The daily cooking activities were not controlled in a way that each household was not requested to cook certain type and amount of foods, instead cooks prepared their normal type of dishes for dinner. The test started around 4 to 6 pm local time every day, a normal time to prepare a dinner in the observed area. The selected farmer households were asked to not discuss with the visiting researchers about the type and amount of food they cooked before the test. Since there was various type of food cooked, each house did the food preparation differently, some washed and cut the ingredients beforehand and others did not. The most common pot used for cooking the base food and stews is called *sufuria* in local language. As the amount of food was not controlled, the size of pot used in each household was also not controlled.

Before each test, fuel used for cooking were prepared by the household. Fuel preparation involved cutting the fuelwood into several pieces after drying it first. The traditional and improved stoves were lit up following the common practice of igniting these stoves in each house. Crop residues, e.g. dried leaves and small branches were used to help ignite the fuel in both stoves. When cooking with improved cookstove, The Gastov, the cut wood pieces were fitted into the canister. Each Gastov was tested at the maximum fuel load as defined by the volume of the canister. Once char was formed by combusting fuelwood in Gastov, it was harvested immediately. If cooking food had not done while fuel was already running out, the same procedure of preparing the Gastov had to be repeated from the beginning. The amount of charcoal was measured after cooking with the improved stove, the amount of fuelwood left after cooking with traditional three-stone open fire was measured.

Cooking observation with three-stone open fire was done at selected farm households on several days after cooking with the improved stove. Cooking with traditional method was controlled, where all households that participated in this combination test had to cook the same type and amount of dishes on the second test. The time for cooking of the day also had to be the same with the first cooking test and was held several days after the first test.

Fuel preparation was integrated with the cooking, in particular cooking preparation phase. The type of fuelwood used for cooking test was not controlled to avoid bias on the test results (Ochieng et al., 2013). To measure the fuel used using TLUD gasifier the fuel weight was measured with a digital scale, before putting it into the canister. The fuelwood moisture content was measured using Testo 606-1 moisture meter. In the meantime, to measure the fuel used for three-stone open fire cooking technique, the mass of pile of fuelwood before cooking and the mass of fuelwood remaining in the pile after cooking was weighed with a digital scale. In the four households that participated in cooking with both traditional and improved stoves on different days, the fuelwood used for both cooking tests was obtained on the same batch of sourcing.

Overall thermal efficiency

The overall thermal efficiency of both cooking techniques was calculated with the following formula (Coffey et al., 2017):

$$\eta = \frac{useable\ energy}{energy\ in\ fuel} = \frac{sensible\ heat + latent\ heat}{chemical\ potential\ energy} = \left(\frac{\sum(m_{fc} \times C_{p,fc}) \times \Delta T + (m_{fc,loss} \times H_l)}{LHV \times m_{f,u}}\right) \quad (3.2)$$

with,

m_{fc} is the mass of food cooked (kg); $C_{p,fc}$is the specific heat of food cooked (kJ/kg°C); ΔT is the temperature difference between the cooked temperature and initial temperature (25°C); $m_{fc,loss}$ mass of food loss during cooking; H_l is the latent heat of vaporisation (2257 kJ/kg); $m_{f,u}$ is mass of fuel used (kg). The specific heat of different food ingredients used for cooking is listed in Appendix B.2.

Net energy consumption of using three-stone open fire

The energy delivered (MJ/capita/meal) by three-stone open fire, ED_{net}, was calculated in order to meet the inventory of LCA (Chapter 3.3) and was calculated from net energy consumption, $EC_{net,3S}$, multiplied with the thermal efficiencies of three-stone open fire (%), η_{3S}, see Equation 3.4. Net energy consumption (Equation 3.3) was determined by multiplying net fuel consumed (kg/capita/meal), F_d, and corresponding lower heating value of the fuel, LHV_{fw}, (MJ/kg), as follows:

$$EC_{net,3S} = F_d \times LHV_{fw} \tag{3.3}$$

$$ED_{net,3S} = EC_{net,3S} \times \eta_{3s} \tag{3.4}$$

The thermal efficiency of three-stone fire was estimated with Equation (4.2). While, the value of LHV was determined previously in sub-chapter 3.3 (also see Appendix B).

Net energy consumption of using gasifier cookstove

There were two measures of cookstove efficiency done as a pyrolytic cookstove served two purposes at the same time in this study, delivering thermal energy to cooking pot and recovering energy in char. The combustion data of biomass and char product was obtained from literatures. The conversion efficiency was calculated with Equation 3.5:

$$\eta_{char} = \frac{m_b \times LHV_{ch}}{LHV_{fw}} \tag{3.5}$$

where m_b is mass-based conversion factor from raw biomass to char (kg/kg) and LHV_{ch} is heating value of produced charcoal (MJ/kg). The conversion efficiency for fuelwood was estimated based on the principle of conservation of energy.

Finally, the energy consumption of TLUD gasifier and energy delivered to cooking pot were determined with the same formula used in determining energy consumption and energy delivered by the traditional three-stone open fire (Equation 3.6 and 3.7).

$$EC_{net,TLUD} = F_d \times LHV_{fw} \tag{3.6}$$

$$ED_{net,TLUD} = EC_{net,TLUD} \times \eta_{TLUD} \tag{3.7}$$

with,

η_{TLUD} is a thermal efficiency of TLUD gasifier cookstove and was also estimated by using Equation. 3.2.

3.2 Life Cycle Assessment

This section describes the relationship between the theoretical concepts of environmental assessment and the methodological technique built for this study. Life Cycle Assessment (LCA) was selected, due to its method of adopting a function-related view. ISO 14040 standard (ISO, 1997, p.2 cited in Heijungs and Suh, 2013) defines LCA as a study of the environmental aspects and potential impacts of a product from throughout its lifespan, from raw material acquisition to its end-of-life, disposal and/or recycling. There are four phases of LCA according to ISO 14040:1997/2006 (Klöpffer and Grahl, 2014), as follows:

- goal and scope definition;
- inventory analysis;
- impact assessment;
- interpretation.

In the following sub-sections, technical frameworks for each phase in carrying out LCA are further described and linked to this study.

3.2.1. Goal and Scope Definition

Goal and scope definition cope with the intended application of the answer to the main research question that the LCA study is supposed to provide. This phase also aims to ensure a consistent study design and make the methodological selections and limitations unambiguous. In this phase, the selection of functional unit and the system boundary are defined (Klöpffer and Grahl, 2014, p.27-57).

Based on the research questions and taking the goal and scope of the Biochar Project into consideration, the goal of this LCA study was, therefore, to analyse the climate impact of cooking with gasifier in comparison with the traditional three-stone fire. The data used in the assessment was collected from both primary and secondary sources. The primary data was collected by the student during the field trip (see Chapter 3.1 for the methodology description of the primary data collection). The secondary data was obtained from the related findings by other researchers in the Biochar Project, related literatures, and governmental documents. The impact categories for this assessment was limited to climate change as a single impact category, due to practical constraints.

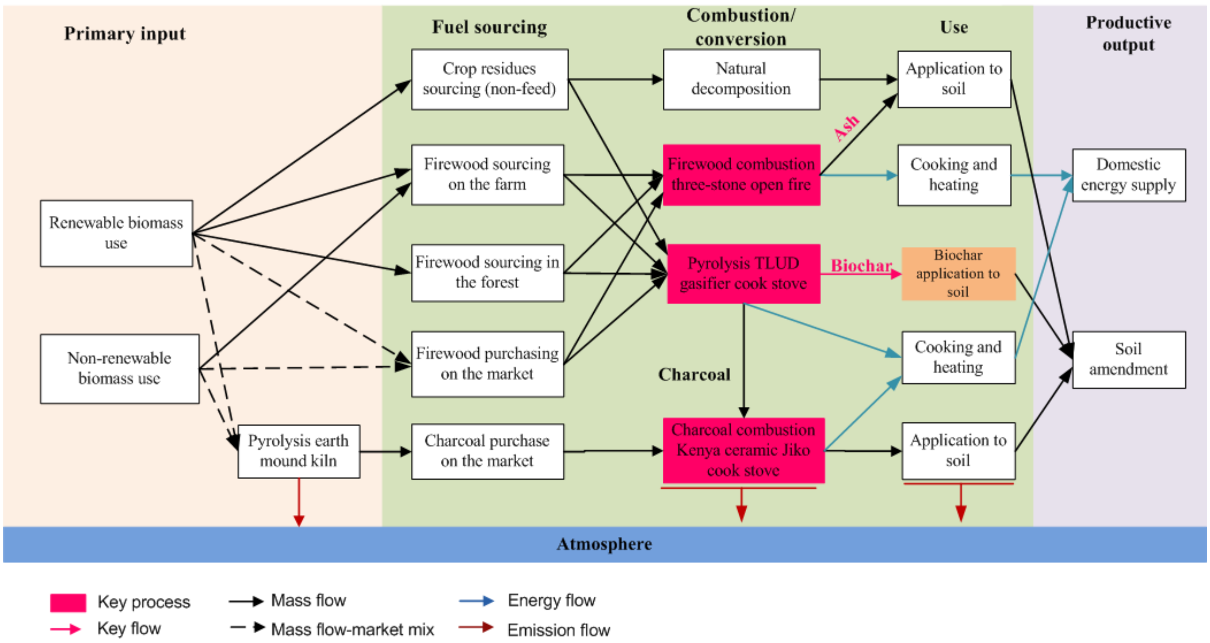

Figure 3. 2. *Schematic overview of processes, flows and services of all three systems under The Biochar Project in Kenya. Adopted from Sieber (2016, p. 32). The reference system uses three-stone fire and produces ash. While the improved system uses TLUD gasifier and is divided into two according to the products, char and biochar systems.*

Functional Unit and Reference Flows

In this study, the assessment was planned for multi-functions of biochar production system in Kenya, which incorporates four co-products of biochar including biomass feedstock management, bioenergy production for cooking, biochar use as soil amendment and carbon sequestration. The functional unit used was net cooking energy consumption per capita per meal, taking into consideration that each observed household consists of different number of family members.

System Boundaries

The system boundaries were developed based on biochar production system in Kenya, specifically in the county of Kwale. The life cycle starts at raw material acquisition, biomass feedstock sourcing on-farm, and ends at the use of the combustion products. As the common practice in Kenya was to hand-cut the fuelwood and carry it home by walking, therefore no relevant impacts of feedstock harvesting or transportation were found. Figure 3.2. illustrates the overall process of the Biochar Project in Kenya consisting of both reference and improved systems, including the two sub-system under the improved system, char and biochar systems, as discussed by Sieber (2016). Under the reference system, the traditional three-stone open fire was used for combustion system, while under the improved systems, the improved cookstove (ICS) namely the TLUD gasifier was used. Within the improved systems, two different sub-systems named after their by-product, char and biochar, were established based on the previous field observations. Under the char system, the char produced by TLUD gasifier was used for cooking and heating purposes. Meanwhile, under the biochar system, the char produced was incorporated into soil, hence referred as the biochar system.

Stand-alone & Comparative LCA

The stand-alone and comparative concepts are not standardised in ISO 14040, however, the distinction is used in this study due to the nature of field assessment results. In a stand-alone LCA, the different parts or processes of one product system are compared (Baumann, 1998). Meanwhile in comparative LCA, the environmental impacts of two different systems are compared (De Bruijn et al., 2004). In both types of methodology, comparison is made by connecting the environmental impact to functional unit (Baumann, 1998). In this study, the stand-alone method is used for comparing the 12 households under the improved system, while the comparative method is used for comparing reference system to improved system.

3.2.2. Life Cycle Inventory Analysis

Life cycle inventory analysis is concerned with identifying all relevant processes, quantification of inputs and outputs required for the system (ISO, 2006 cited in Klöpffer and Grahl, 2014). A final step of this phase is the accumulation of the chemicals emissions and the natural resources extractions over the entire product system. The inventory table is referred as these accumulated emissions and extracted final table (Heijungs and Suh, 2013). The processing data was collected from the primary and secondary data, and reported relative to the functional unit.

Modelling Principles and Framework

In addition to identifying all the processes, LCI work also means to model the system in the inventory by accurately connecting and scaling the data towards the functional unit. The modelling comprises solving multi-functionality of processes in the system (Wolf et al., 2010, p. 154). Multi-functionality of a process or a product is considered when a process or a product provides more than one function at a time. There are two ways of solving the multi-functional problems by system expansion and allocation. According to ISO 14044 (ISO, 2006 cited in Pelletier et al., 2015, p. 75), allocation is "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems". The system expansion is done by changing or expanding the system boundary of the study. By following the hierarchal structure, ISO (2006) as cited in Pelletier et al. (2015) suggested multi-functional problems method in order of preference, as follows:

1. allocation shall be avoided wherever possible by dividing the unit process into sub-process or by expanding the product system (system expansion);
2. allocation based on underlying physical relationship;
3. allocation based on other relationships between products and functions.

The actual biochar system analysed in this study involves multifunctional products and processes at several stages, both in the form of parallel functions (e.g. fuel combustion for cooking, lighting and space heating) and following functions (i.e. biomass use for energy provision and soil amendment). According to the ISO 14044 recommendation, this study solved the multi-functional problems by dividing the unit process into several sub-processes. In the previous study by Sieber (2016), the biochar for soil amendment was not further quantified as it was considered as a non-mandatory service. In contrast, this study quantified the biomass for soil amendment as a sub-process. Similar to study by Sieber (2016), space heating was not quantified as a function due to consideration of space heating as a secondary purpose of cooking process. This study only addressed two options to use char, charcoal for energy provision and biochar for soil amendment to examine the biochar system based on real conditions in Kwale County, Kenya.

The modelling approach used in this study is attributional LCA. Attributional approach to LCI is identified by its focus on describing the environmentally significant physical flows to and from a life cycle and its sub-systems (Curran et al., 2005). Attributional modelling portrays the system as it can be observed (historical, current, or future), connecting the single processes within the technosphere. In contrast, consequential LCA is identified by its focus to explain how environmentally relevant flows will change the potential decisions (Finnveden et al., 2009, p. 3; Wolf et al., 2010, p. 153-183). Using site-specific data from field studies leads to more accurate and detailed assessment, also to get better understanding of the potential environmental impacts of each sub-process (Jørgensen et al., 2008; Ross and Evans, 2002). In addition to site-specific data, the secondary data from larger studies and governmental documents were used to fill data gaps and to check consistency.

According to the goal and scope of this study, the LCA should produce locally relevant results. The first step of LCI modelling was to establish a model farm which served as a reference system or baseline of the study. As mentioned, the data used in this study relied on site-specific field data collected for this study (See Chapter 4) and field data from the Biochar Project whenever available. Depending on the data availability, the assessment used responses of all 12 households/farmers that participated in the cooking observation whom also participated in the biomass survey. These data were contrasted with literature data from a larger scale study to identify potential errors. Any data gaps were filled by data from regional, Kenya specific or Eastern Africa sources, and generic data was avoided.

The modelling framework for this study was adopted from the study by Sieber (2016). The inventory analysis related to the climate impact of the systems covered three modules, as follows:

1. Feedstock module: quantified the available biomass feedstock for energy provision and biochar co-production purposes, also called pyrolysis cooking, at the farm level.
2. Cooking module: identified the available fuelwood types; quantified the production and transportation of the cookstoves; assessed the thermal energy of the cookstoves, emissions during the cooking process, and the char product and its quality.
3. Soil module: assessed the stability of the carbon in the biochar, the recalcitrant and labile carbon fractions, to see the behaviour of biochar; quantified the crop response upon biochar application as a soil amendment.

Carbon Accounting in Biochar System

The role of biochar in climate change mitigation relies on the stability of C that it contains. It is important to consider exposure to solid, liquid, and gaseous products of pyrolysis at all phases of production and in the application of biochar to soil (Sohi et al., 2010). In this study, however, the assessment only considered the solid and gaseous products of pyrolysis process. Sohi et al. (2010, p. 74-75) and Whitman et al. (2010) recommend the full assessment model of conducting scenario comparisons of feedstock and char making technology. By taking a feedstock approach, the fate of the feedstock biomass would have been without the production of biochar can be understood. It is also suggested by Sohi et al. (2010) that to identify the functional behaviour of biochar and the impact of biochar on soil-based GHGs, the assessment of carbon and nitrogen cycles in soil with and without biochar is necessary. This study considered the available feedstock approach as suggested by Sohi et al. (2010) and Whitman et al. (2010). The offsetting issues for carbon accounting with biochar system addressed in this study (Gaunt and Cowie, 2009), as follows:

1. Permanence – to determine the duration and the mechanism that will the C offset be secured. Natural decomposition and traditional biomass combustion are assumed to release all feedstock carbon, or if it is incomplete combustion, the recalcitrant C fraction is left in the ash. By increasing energy efficiency or reduced fuel consumption, unused living carbon stocks are identified stable, therefore, aligns with the conservative principles of carbon accounting, despite not directly decreasing atmospheric CO_2 (Whitman et al., 2010). In the biochar production system, by assuming that the carbon in biochar is stable, conversion of organic resources to pyrolysis would lead to a permanent offset against future atmospheric CO_2 (Sohi et al., 2010, p. 55). Also, by enhancing the C sequestration strategies, biochar would overcome the permanence issues (McCarl et al., 2009).
2. Leakage – to consider the emissions that are indirectly attributable to the project and appear outside the project boundary. This study addressed one of the risk source of leakage which was the poor estimation of fraction of non-renewable (fNRB) biomass from which the fuel comes. Non-renewable biomass can be defined as biomass that

harvested faster than it grows back. Renewability addresses the biogenic carbon emitted during C sequestration or combustion is assumed to be equivalent of CO_2 uptake during plant regrowth. (Whitman et al., 2010, p. 102)

3.2.3. Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is the third phase where the results of inventory analysis is further processed and interpreted with regards to environmental impacts and societal preferences (De Bruijn et al., 2004). According to the ISO 14040, LCIA is comprised of five steps, as follows (Hauschild and Huijbregts, 2015):

1. Selection – the impact categories, category indicators, and characterisation models are selected in accordance to the goal of the study.
2. Classification – the LCI results, including the resource consumption and emissions, are assigned to the relevant impact categories among those chosen under Selection step.
3. Characterisation – category indicator results is calculated, where the amount for each elementary flow assigned to an impact category is multiplied with characterisation factor.
4. Normalisation – an optional step where the magnitude of category indicator results in relation to reference information is calculated resulting scores of common scales from different impact categories.
5. Weighting – another optional step where weighting factors are applied based on value of selections and represent the significant assigned to each of the impact categories.

The fourth and fifth step, normalisation and weighting, respectively, were not used in this study as they are optional.

Selection and Classification

Following the recommendation by ISO 14044 (ISO, 2006 in Hauschild and Huijbregts, 2015), the selection of impact categories should be consistent with the goal and scope of this study. Therefore, a midpoint indicator of climate change was selected to be modelled, due to the goal of this study was to investigate the climate change impacts of biochar system. Climate change is defined as the impact of human emissions on the radiative forcing (RF) of the atmosphere. Climate change midpoint indicator is relevant to the areas of protection of human health and natural environment, aligned with the goal of this study. (Anon., 1999; De Bruijn et al., 2004).

The cut-off criteria for the input and output data was established and if input our output was less than 5% of the energy or mass of the climate impact per functional unit. These data were not included if they were not available.

Characterisation

In this study, the 100-year global warming potentials (GWP) of carbon dioxide, methane, and nitrous oxide from Intergovernmental Panel on Climate Change (IPCC) 2013 (Myhre et al., 2013) were used to estimate the climate change impacts of each process in the biochar system. All the characterisation factors selected in this study included climate-carbon feedbacks in response to the reference gas CO_2 as recommended by IPCC and as presented in Appendix D.

Impact assessment model

This study fully accounted biogenic carbon dioxide as performed by Scholz (2014, p. 71-132), in the following manner: the carbon uptake during feedstock growth for sustainable feedstock harvest and for unsustainable feedstock, in this study referred as renewable and non-renewable biomass, respectively; the carbon emissions during thermal conversion; and the carbon sequestration in the biochar.

While GWP is generally used to account for emissions of GHGs included in the Kyoto protocol (including CO_2, CH_4, N_2O and other long-lived gasses), GWP is not ideal to account the warming impacts of short-lived climate forcing agents. A more precise and reliable evaluation of climate change metric is the Global Warming Commitment (GWC). The GWC also describes the effects of the past, present and future evolution of GHGs content in the atmosphere (Frolkis et al., 2002). Therefore, the calculation of the climate change applications of a cooking activity was expressed as the net emissions of GHGs, $\Sigma_i GHG_i$, from the cooking activity (CO_2–eq) following recommendations by Smith et al., (2000, p. 751), as follows:

$$GWC = (\Sigma_i GHG_i)(GWP_i) \tag{3.8}$$

where *i* refers to the GHGs, GWP_{100} for each GHGs is listed in Appendix D. The emission factor each type of fuel/cookstoves combination used is specific, therefore, determining the GWC was separately calculated for each combination of fuel and stove. In a similar study by Sieber (2011), two sets of emissions were defined according to level of uncertainties of the different gasses effects to radiative forcing (RF). In this study, both emission sets for basic and full set of GHGs and defined by Sieber (2011) was assessed.

By doing a sustainable or renewable harvesting of biomass, emissions of CO_2 are completely recycled, hence, there is no net increase in GWC from CO_2. For products of incomplete combustion (PICs), renewable harvesting only affects GWC by removing the portion of each gas owing to its eventual conversion to CO_2 in the atmosphere. On the other hand, in non-renewable harvesting, all the carbon in biomass is a net addition to the atmosphere.

Since the atmospheric mechanisms of basic (well established) set of GHGs (CO_2, CH_4, and N_2O) are thoroughly studied and its midpoint is independent of exposure and regional differences, therefore the characterisation phase for basic set of GHGs has been associated with low uncertainty (Sieber, 2016). The GWC for basic set of GHGs (GWC_{set1}) is determined from fuel consumption (FC), the emission factor of each climate forcing gas i (EF_i) and its characterisation factor for the renewable (RB) and non-renewable (NRB) fuel fraction (GWP_i), as follows:

$$GWC_{set1} = (FC)\left(\sum_{i=1}^{n} EF_i\left((f_{NRB})(GWP_{NRB,i}) + (1 - f_{NRB})(GWP_{RB,i})\right)\right) \tag{3.9}$$

where, FC is household fuel consumption (kg drymass) and EF_i is the emission factor of each climate forcing gas (g pollutant/kg).

The second set,GWC_{set2}, studied the five gasses to give better estimation of full climate impact. The extended gasses added to the basic set of GHGs are CO, NMHCs, and PM, which are also known for their significantly high uncertainties due to less-mixed and less understood in their effects on RF (Forster et al., 2007). The GWC of the second set is only determined from the non-renewable biomass characterisation factors adopted from the study by Sieber (2016). A 20-years time horizon was calculated and compared to the selected 100-years to avoid misinterpretation of short-lived climate forcers. Particularly in this set, using a 20-years time horizon simplifies the attempt to model the problematic effects of open biofuel combustion in a more comprehensive manner (Sieber, 2016). The GWC of the second set, also referred extended set, is defined as follows:

$$GWC_{set2} = (FC)\left(\sum_{i=1}^{n} EF_i(GWP_{NRB,i}) - 3.66C_{em}(1 - f_{NRB})\right) \tag{3.10}$$

where C_{em} is the feedstock carbon emitted determined from the total carbon content per kg of fuel by subtracting the carbon based conversion factor from raw biomass to char and ash. 3.66 is the scaling factor after transforming the carbon emitted to CO_2.

Carbon sequestration in biochar

The characterisation for the extended biochar system for the partial sequestration of carbon in soil (the fraction of recalcitrant f_{RC}) , and of the remaining fraction of labile carbon (1-f_{RC}) as CO_2. The release of carbon from the renewable fraction have no net climate impact and thus left out. However the release of carbon from the non-renewable fraction has a positive net climate impact and therefore calculated as $(f_{NRB})(1 - f_{RC})$. In contrast, the storage of carbon from the renewable fraction has a negative net climate impact and calculated as $(1 - f_{NRB})(f_{RC})$. Starting from the fuel household consumption FC, this is calculated from the share of carbon not emitted during conversion $(1 - C_{em})$.

$$GWC_{bc} = (FC)(1 - C_{em})(3.66)((f_{NRB})(1 - f_{RC}) - (1 - f_{NRB})(f_{RC})) \tag{3.11}$$

Modelling

The analysis and modelling were carried out with Microsoft Excel 2013. The data processed and analysed including the feedstock consumption, cooking energy, biochar application, and pollutant emissions. By implementing Equations 3.9 to 3.11, the aggregate climate change impacts for different type of emissions and timeframes were determined. The inventory data and results of the LCIA were analysed using pivot tables to classify the impacts per system, per type of emissions, and per time frame.

3.2.4. Interpretation

Life cycle interpretation is the last phase on LCA in which the results of the modelling and analysis, as well as the assumptions and choices made during the course of analysis are concluded and recommendations are made according to the objective of the study (Klöpffer and Grahl, 2014; De Bruijn et al., 2004). The interpretation proceeds through three sequential activities, as follows (ISO 14044 in Wolf et al., 2010, p. 285-306):

1. *identifying the significant issues* – the significant quantitative differences usually involving data uncertainties. The type of uncertainties can be found on different phases of LCA, e.g. functional unit and system boundaries in methodological selections and characterisation factors in impact assessment.

2. *evaluating the issues with regard to their sensitivity on the results of LCA* – there are three techniques that can be considered for this evaluation, namely completeness check, sensitivity check, and consistency check. Completeness check is necessary to fill in gaps during the inventory with optimised data. Sensitivity check estimates the uncertainties in the results due to data quality, cut-off criteria, selection of allocation rules and selection of impact categories. Lastly, consistency check refers to the first phase of LCA, particularly, goal and scope definition.
3. *formulating the conclusions and recommendations based on the results of evaluations*.

By processing and modelling the impact assessment in Microsoft Excel 2013, it allows to test different assumptions and selections made during the first to the third phase of LCA without recalculating the results if uncertainties are found. The sensitivity analysis were also done in this study involving several parameters, as follows:

- Stable carbon content of biochar
- Fraction of non-renewable biomass (fNRB)

3.3 Case and System Inventories

This section describes the overview of all alternatives into two different systems compared in the LCA, referred as the reference and the improved systems and was utilised as Life Cycle Inventory (LCI).

3.3.1 Cooking System in Waa Ward, Kwale

The systems used in Kwale were the reference system and the biochar system. The improved system or the biochar system was referred to the application of char produced by the improved cookstoves, The Gastov, in Kwale was only as a soil amendment (biochar) and not for cooking and heating purposes (charcoal). In the reference system, cooking was carried on by using three stone open fire. In Kwale, it was found that the by-product of cooking with the three-stone open fire, ashes, was not applied to soil but rather left unused.

3.3.2 Feedstock Module

The primary biomass used in the study area, Waa Ward in Kwale County was firewood. The quantity of available feedstock for cooking with both cooking techniques were obtained during biomass availability measurement (see results on chapter 5). The type of biomass used as a cooking fuel was identified during Kitchen Performance Test (KPT).

The woody biomass, firewood, used as a feedstock are obtained through pruning trees branches. Pruning is a common farm management practice to encourage growth of the tree, in particular Casuarina trees, where the branches were usually pruned once in a year to let the tree grows straight up. For the other species of trees, pruning was commonly done just before or during the planting season to clear the branches and to create more space for planting. Based on the questionnaire, it was discovered that the on-farm pruning activity was usually done before the planting season starts, which means that pruning was normally done once in a year. The available pruned biomass for cooking was calculated by subtracting the biomass needed for other purposes in the household and farms, such as construction materials, from the total available pruned biomass. Under both systems, all pruned biomass required for cooking with either three-stone open fire or TLUD gasifier was assumed to be collected in the farm (See Figure 3.3 and Figure 3.5). Which was correct in most households. Based on the questionnaire, only one household pruned outside their farm from time to time as the wood preferred for cooking are not available on their farm.

To clarify that the pruned biomass collected on the farm is a “renewable” biomass source, short-interview was done with the participants during the biomass availability measurement. In this study, pruned biomass collected on the farm could be classified as renewable when biomass sources follow the harvesting practices that allow regeneration of the biomass. Based on the KPT, biomass measurement, and questionnaire, most of the farmers indicated that the woody biomass used as feedstock during the non-harvesting season were indeed renewable.

The inventory started with assessing the feedstock module. Since the data were obtained through the field study, the inventory of feedstock module is presented in Table 4.7 under the results chapter (see Chapter 4.2).

3.3.3 Reference system: traditional practice

The reference system is the current traditional practice regarding feedstock management, fuel consumption, cooking technique, and the use of combustion residues in the studied area. Figure 3.3. illustrates the system boundary of the reference system includes the processes and flows investigated in the studied area. The system boundary was narrowed down from the general system boundary described on Chapter 3.2.1. based on the field study. Furthermore, the use of combustion residue (ash) as a soil amendment was omitted from the system by considering the real condition in the studied area.

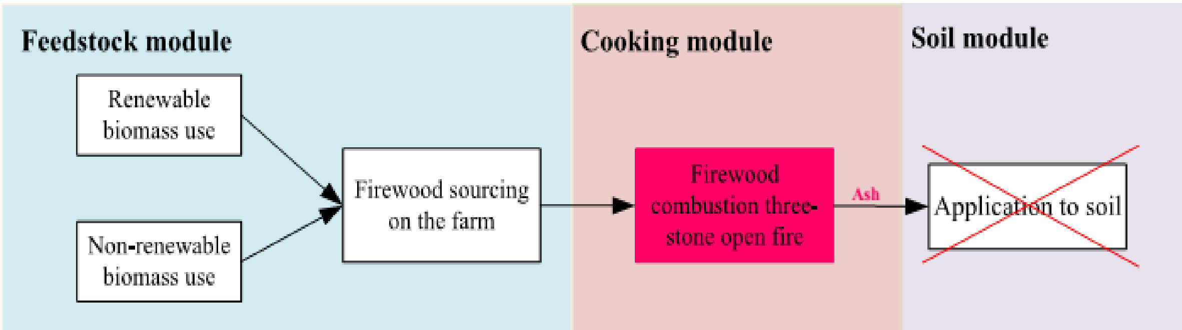

Figure 3. 3. *System boundary of the reference system discovered in Waa Ward, Kwale*

Cooking Module

Figure 3. 4. *One of the participant cooking with traditional three-stone open fire during field observation in Kwale.*

As seen from Figure 3.4., the reference system assessed the performance of three-stone open fire under cooking module, which discussed below.

Cooking method

The traditional cooking practice in rural households in Kenya is use of three-stone open fire for cooking (Figure 3.4). Most of the participating households cooked outside their main houses, and thus, space heating, the other application of three-stone open fire as described by Sieber (2016) was not applicable in this study.

Fuel use and energy consumption

The quantity of fuel used and energy consumption per capita per meal in a household was estimated using the data obtained during Kitchen Performance Test (KPT). Originally, the results from KPT were shown in household basis and one dinner (meal) basis. To obtain the value on functional unit basis, per capita, the parameter was divided by the total amount of people in the household. The amount of fuel used and energy consumed in the house is presented in Table 4.8 under the results chapter.

Cooking emissions estimations

The emissions from combustion process in three-stone open fire were calculated based on published data from cooking tests and products of incomplete combustions. The carbon emitted was calculated from the amount of biochar yield per capita per meal, and a biochar carbon content of 75.6%. In order to simplify the calculation, the same biochar carbon content used by Sieber (2016) was used in this study for all type of woody biomass.

The carbon balance equation, Equation (3.12) was used in order to estimate the carbon-based GHG emissions. The carbon balance was calculated based on the assumption that during combustion, the total carbon content of the fuel (TC) is converted to gas (CO_2, CH_4, CO, NMHCs), particulate matter (BC and OC) and solid residues (char) (Bailis et al., 2003; Sieber, 2016; Smith et al., 2000).

$$TC = C_{CO_2} + C_{CH_4} + C_{CO} + C_{NMHC} + BC + OC + C_{char} \quad (3.12)$$

The emission factors were expressed as pollutant mass (gram) per kg of dry fuel for each combination of three-stone open fire and fuelwood and are listed in Table 3.1. The emission factors for *Azadirachta indica* and *Melia azedarach* were taken from the emissions factors of *Eucalyptus* reported by Smith et al., (2000, p. 752) and calculated by Sieber (2016). It was considered similar due to the close similarities in carbon properties between the three species of trees (for *A. indica* see Mensah et al., 2017 and for *Eucalyptus* see Smith et al., 2000). *A. indica* and *M. azedarach* were considered similar since they belong to the same botanical family, Meliaceae. The energy content between the three trees were found to be on the same range of 17-19 MJ/kg (for the energy content obtained from the field can be seen in Appendix B and the energy content for *Eucalyptus* see Perez et al., 2006). Meanwhile, the emission factors for *C. equisetifolia* were obtained by calculation referring to emission factors *Acacia* reported by Bailis et al. (2003).

The emission factor for aerosols are usually listed as total suspended particles (TSP) either in pollutant mass basis or in carbon mass basis (TSPC), or as particulate matter (PM), either PM_{10} or $PM_{2.5}$. The emission factors of black carbon (BC) and organic carbon (OC) (Equation 3.13 and 3.14) was determined by using typical ratios for woody biomass combustion in cookstoves with all values in carbon mass basis (Roden et al., 2006), as follows:

$$\frac{BC}{TPSC} = 0.3000 \tag{3.13}$$

$$\frac{OC}{TPSC} = 0.3000 \tag{3.14}$$

Meanwhile, the emissions of sulphur dioxide (SO_2) was estimated by using the assumptions used by Sieber (2016), calculated from sulphur content of each species of fuelwood. The calculated emission factors of combination of three-stone open fire and fuelwood used for the assessment of cooking module are shown in Table 3.1.

Table 3. 1. *Three stone-open fire performance per kg of dry fuelwood*

	Fuelwood	**Carbon balance (g C/kg fuelwood)**			**Pollutant (g/kg fuelwood)**								**Renewable Biomass credit (g CO_2/kg-fuelwood)**
		Fuel carbon in	**Solid carbon out**	**Carbon emitted**	**CO_2**	**N_2O**	**CH_4**	**CO**	**NMHCs**	**BC**	**OC**	**SO_2**	
Household 1	*C.equisetifolia*	470	1.46	468	1533	4.50	0.000	69.0	2.40	0.330	0.770	0.200	1715
Household 2	*A. indica*	456	1.20	455	1536	2.83	0.070	60.2	7.98	0.280	0.660	0.400	1667
Household 4	*M. azedarach*	456	1.20	455	1536	2.83	0.070	60.2	7.98	0.280	0.660	0.400	1667
Household 7	*A. indica*	456	1.20	455	1536	2.83	0.070	60.2	7.98	0.280	0.660	0.400	1667

Soil Module

The utilisation of by-product from combustion process was assumed to be none in this study, and thus, the 'no application of biochar' scenario was applied in this case. Table 3.2. lists the agriculture emissions (g/kg product) in four participant farms. Cool Farm Tool version 2.0 was used to estimate agriculture emissions and the tool is further explained under the Improved System section.

Table 3. 2. *Agriculture emissions when no biochar applied to soil*

	Biochar application rate (kg/m^2)	Fertiliser (kg)	Yield (kg/m^2)	Agriculture emission (g/kg product)	
				CH_4	N_2O
Household 1	0.000	0.000	0.050	4.61E-05	0.000
Household 2	0.000	0.000	0.050	5.42E-05	0.000
Household 4	0.000	1.00	0.120	2.11E-05	0.000
Household 7	0.000	0.000	0.050	4.94E-05	0.000

3.3.4 Improved system

Based on the observation, the improved system was narrowed down to only one system. The system boundary for improved system is illustrated in Figure 3.5. In the improved system, the harvested biochar was applied to agricultural soils as soil amendment. The construction and transportation of the cookstove were considered in the system (Table 3.3.).

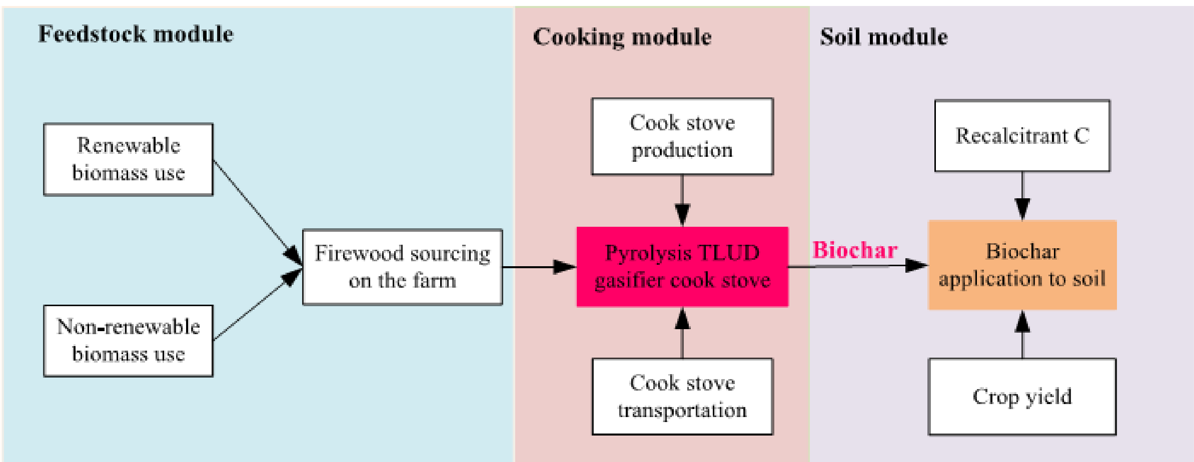

Figure 3. 5. *System boundary of the improved system discovered in Waa Ward, Kwale*

Cooking Module

As illustrated in Figure 3.5., the cooking module under the improved system involved wider scope than the reference system as it included the production and transportation of cookstoves. Table 3.4. lists the data used for inventory which includes the cooking performance and emission factors of combination stove-fuel.

Figure 3. 6. *A participant cooked with TLUD gasifier during observation in Kwale*

<u>Cooking method</u>

The Gastov, a TLUD gasifier cookstove, was investigated under the improved system. Figure 3.6. shows the picture of one of the participant cooking with Gastov taken during observation in Kwale. Based on the observation, it was found that the gasifier cookstove averagely used for cooking only once in a day.

<u>Fuel use and energy consumption</u>

By using the same method used under the reference system, the quantity of feedstock consumed per capita per meal in a household under the improved system was obtained. The amount of fuel used and energy consumed by The Gastov from field sudy is described in Table 3.1.

<u>Cookstove construction</u>

The Gastov, a TLUD gasifier stove, was built at KIRDI, Nairobi, Kenya and then distributed to some counties in the country including Kwale. Based on the results from unstructured interview with the innovator of the stove at KIRDI, the local production would not be anticipated in the near future. While, the three-stone open fire was built locally, using big rocks found nearby. The mass of the Gastov is approximately 13 kg, excluding the canister. The main material to build Gastov was stainless steel 304, imported from China by freight to the coast at Mombasa and then transported by road to Nairobi, and was shipped with cold rolled technique, assuming that the weight of one roll of 4000x2000x4.00 mm was 272 kg. It was assumed that the mass of stainless steel used for a Gastov was approximately 2.25 kg (Scholz et al., 2014). The lifetime of the Gastov was assumed to be four years, based on a typical lifetime range of improved biomass cookstoves (Scholz et al., 2014; Adkins et al., 2010). The transportation emission of the stainless steel was accounted by using the recommendation average value for deep-sea shipping transport mode is 8.4 g CO_2/tonne-km (McKinnon, 2011). While, the emissions data from road transportation in Kenya were not available, hence, emissions factor of European transport was used from McKinnon (2011). The recommendation value for average CO_2 emission factor for road transport mode is 62 g CO_2/tonne-km. This recommended value is based on average load factor of 80% of the maximum vehicle payload and 25% of empty running.

<u>Cookstove transportation</u>

The Gastov was transported from Nairobi to Kwale with road transportation, and it was assumed that farmers walked from home to pick up the stoves from where the stoves were dropped off at Kwale. The distance from KIRDI in Nairobi to Waa Ward, Kwale is 500 km one way. The emission for transporting the Gastov was estimated with the same method with the road transportation of raw materials from Mombasa to Nairobi.

Transportation emissions estimation

The transportation of raw materials to build cookstove in Nairobi and shipping cookstoves to Kwale County were included in this work. The emission calculation could be done in two methods, activity-based approach and energy-based approach. In this study, the activity-based approach was used due to the availability of data. The emission of transport using activity-based approach uses the following formula (Cefic-ECTA, 2011):

$$CO_2\ emissions = Transport\ volume\ by\ transport\ mode \times\ transport\ distance \times\ CO_2\ emissions\ factor\ per\ tonne - km\ per\ transport\ mode \tag{3.15}$$

The transportation emissions were calculated for one cookstove and are listed below in Table 3.3.

Table 3. 3. *Transportation emissions calculated for transporting construction material to Kenya and the Gastov to Kwale*

Transportation	Unit	GHG emission (kgCO2)
Freight transport of raw materials from China to Mombasa	txkm	2.99E-05
Road transport of the Gastov from Nairobi to Kwale	txkm	7.34E-04

Cooking emission estimation

As reviewed from existing literature, the principle work of TLUD gasifier is by separating gas conversion and combustion in two different phases, therefore leading to higher fuel efficiency and lower product of incomplete combustion (PIC) emissions than traditional three-stone open fire. As data obtained during KPT for this study was not ready yet to be included for calculation, this study followed calculated emission factors by Sieber (2016) and Scholz et al. (2014). In both studies, the emissions were calculated based on data from gasifier cookstove from MacCarty et al. (2008) and emissions to ratios of CO_2 and PIC were compared using the same method used in Whitman et al. (2011). The investigated in MacCarty et al. (2008) was similar to TLUD in respect to the fire ignition technique, top-lit. The molar emission ratios found in results section of study by MacCarty et al. (2008), was calculated for a household gasifier cookstove fuelled with *Pseudotsuga menziesii* species of wood, or commonly known as Douglas fir. After that, the emission ratios were converted into pollutant mass and scaled in accordance with the carbon content of different fuelwood. As mentioned in the reference system, *Eucalyptus* for *A. indica* and *M. azedarach* and *Acacia* for *C. equisetifolia*. The emission factors of N_2O was estimated with the same method as in the reference system, by using an assumption of 20% to 80% distribution between production and consumption of char, respectively. The estimated emission factors of combination of TLUD gasifier and fuelwood used for inventory of the improved system’s cooking module are shown in Table 3.4.

Table 3. 4. *TLUD gasifier cookstove performance per kg of dry fuelwood*

	Fuelwood	Carbon balance (g C/kg fuelwood)			Pollutant (g/kg fuelwood)								Renewable Biomass credit (g CO_2 /kg-fuelwood)
		Fuel carbon in	Solid carbon out	Carbon emitted	CO_2	N_2O	CH_4	CO	NMHCs	BC	OC	SO_2	
Household 1	*C.equisetifolia*	470	140	339	1001	1.30	0.000	29.0	3.90	0.050	0.320	0.080	1208
Household 2	*A. indica*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1667
Household 3	*C.equisetifolia*	470	134	336	1001	1.30	0.000	29.0	3.90	0.050	0.320	8.00	1231
Household 4	*M. azedarach*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1169
Household 5	*C.equisetifolia*	470	141	329	1001	1.30	0.000	29.0	3.90	0.050	0.320	8.00	1036
Household 6	*C.equisetifolia*	470	141	329	1001	1.30	0.000	29.0	3.90	0.050	0.320	8.00	0.00
Household 7	*A. indica*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1667
Household 8	*A. indica*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1169
Household 9	*A. indica*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1169
Household 10	*C.equisetifolia*	470	160	309	1001	1.30	0.000	29.0	3.90	0.050	0.320	8.00	0.00
Household 11	*A. indica*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1169
Household 12	*A. indica*	456	137	319	1095	1.64	0.040	30.0	6.87	0.060	0.350	0.080	1169

Soil Module

Assessing soil module under the improved system was more complicated, since biochar was applied to the farm. As shown in Figure 3.5, the soil module consists of recalcitrant biochar and crop response. Table 3.7. shows the inventory data required for assessing the soil module.

Carbon in the Biochar

To simplify, a carbon content of 75.6% on a dry basis in all the wood chars produced by TLUD gasifier (Sieber, 2016, p.46). In other words, for 1 kg of the wood biochar, 0.756 kilogram is carbon. Of this carbon, the majority is in a highly stable state and has a mean residence time of 1,000 years (Lehmann et al., 2009). For this study, a conservative estimate of 80% recalcitrant carbon was assumed (Lehmann et al., 2009), and the remaining 20% of the carbon is labile and emitted as CO_2 in the short term.

Biochar soil application and agriculture emission

The soil application of biochar data was obtained from field trials on 2017 as all the farmer participants in this study also participated on 2017 field trial. The data from 2017 field trials consisted of biochar application rate, fertiliser application rate, and crop response. For the field trial, the amount of biochar applied was not controlled. In other words, farmer in each household was free to select the amount of biochar applied to the study plot. The study plot area was 4x5 metre. The data of biochar application to soil and maize crop response are listed in the Life Cycle Inventory (Appendix C). It was assumed that biochar soil application model was equal to cooking-method model, with labile carbon fraction was being fully oxidised to CO_2.

To accurately assess the biochar effect on agronomy, local data from long-term field study would be required. As the local data from the Biochar Project was not available when this study was carried out, a conservative assumption of 500 years of mean residence time (MRT) was selected as recommended by Whitman et al. (2010).

The soil emission data was obtained from simulating 2017 field trials data in Cool Farm Tool version 2.0. Cool Farm Tool is an open source farm focused GHG calculator and can be freely accessed at https://coolfarmtool.org/coolfarmtool/. It has been used by several studies to determine GHG on farm/farmer and geographical based calculation (Haverkort and Hillier, 2011; Ortiz-Gonzalo et al., 2017; Hillier et al., 2011). Cool Farm Tool is updated with varied farming databases from different countries, including Kenya. Ortiz-Gonzalo (2017) utilised Cool Farm Tool to determine GHG balances and hotspots in smallholder farmers in Central Kenya. Table 3.5. lists the selected parameters for calculating farm emission in Kwale.

Table 3. 5. *The selected parameters input to model farms in Kwale in Cool Farm Tool (Cool Farm Tool 2.0, 2018)*

Item	Selected option
Climate	Temperate, tropical
Soil texture	Sandy, loamy, coarse
Soil organic matter	1.72% < SOM <= 5.16%
Soil moisture	Dry
Drainage	Poor
pH	5.5 < pH <=7.3
Fertiliser	Compound NPK – 15% N/ 15% K_2O/ 15% P_2O_5 (mixed-acid process) (0% N)

The basis for estimating the soil emission was emission of mass of the biochar product per square metre of the maize field (kg/m^2). The biochar applied to the trial plots was products of the conversion process using TLUD gasifier cookstove, harvested once the fuelwood was fully carbonised. When inputing the field trials data to Cool Farm Tool, the biochar rate, fertiliser rate, and grain yield, were all adjusted to the functional unit of this study, per capita per meal. The type of fertiliser used by the farmers in Kwale County was assumed to be NPK based on the soil analysis performed by Egerton University in Nakuru, Kenya (Andae, 2014). The maize planting and harvesting dates were set on March 2017 and July 2017, respectively. The soil characteristic in Kwale is Coarse Sandy.

For calculating climate change impacts of CH_4 and N_2O emissions and soil organic C change in the farm with biochar amendments, developed by Zhang et al. (2012), and applied to the Equation (3.8). As described, only two GHG emissions were accounted for, therefore i are CH_4 and N_2O. GWP (kg CO_2-e/m^2) is the total emission in CO_2-equivalents per square metre; Hence, calculating GHG_i, the total emission per square metre (kg/m^2), is as follows:

$$GHGI = GWC/Y \tag{3.16}$$

GWC is the overall total emission of CH_4 and N_2O, Y is the grain yield of maize (kg/m^2), and GHGI is the total overall emission intensity with grain production (kg CO_2-e/kg). Table 3.6. lists the emissions of biochar as soil amendment in all participating households.

Table 3. 6. *Emission factors of biochar (input) to the same model as fuel-stove combination (cooking module) per kg of dry fuelwood*

	Stable carbon (%)	Carbon balance (g C/kg fuelwood)			Pollutant (g/kg fuelwood)			Renewable Biomass credit (g CO_2/kg-fuelwood)	Biochar credit (g CO_2/kg-fuelwood)
		Fuel carbon in	Solid carbon out	Carbon emitted	CO_2	N_2O	CH_4		
Household 1	80.0	756	0.000	151	554	0.000	0.000	554	2216
Household 2								554	2216
Household 3								554	2216
Household 4								477	1906
Household 5								0.000	0.000
Household 6								554	2216
Household 7								554	2216
Household 8								554	2216
Household 9								554	2216
Household 10								0.000	0.000
Household 11								554	2216
Household 12								554	2216

Chapter 4: Results

This section presents the results of the study, both from the observation at the field and the climate change impacts of two cooking system, and thus, is divided into two chapters.

4.1 Fieldwork

Under the following sub-sections, the results from data obtained in the studied area are presented and analysed.

4.1.1. Biomass availability

The typical farming household is composed of the homestead, centrally located and typically surrounded by trees. The farms range in size from 1 to 3.25 ha with an average of farm size 2.33 ha. The rests of the farms are divided into different size of plots. The main agricultural activity is maize crop, intercropped with green vegetables. The green vegetables are usually grown closest to the house. Other trees are usually planted or naturally grown scattered within the farm. In the study area, it is unusual to build a fence around the house as a boundary due to local culture, however, some households started fencing the area with shrubs or fences made from branches of the neem tree. Total pruned biomass availability varied significantly depending on several factors, including area of the farm, the age of the tree, and the farm management. In most farms, the pruned wood was solely used for cooking purpose, with no competing uses within the farm based on the survey and observation.

Table 4. 1. *Species of trees identified on-farms of participating households in Kwale, Kenya*

Trees on the farms at Kwale, Kenya			
Swahili name	**Common name**	**Binomial name**	**Assigned name**
	Neem	*Azadirachta indica*	a
	Casuarina	*Casuarina equisetifolia*	b
	Mango	*Mangifera indica*	c
	Cashew Nut	*Anacardium occidentale*	d
	Leucaena	*Leucaena leucocephala*	e
Mkilifi	Chinaberry	*Melia azedarach*	f
Mrabai		*Senna siamea*	g
Mbambakofi		*Afzelia quanzensis*	h
	Soursop	*Annona muricata*	i
Mbokwe		*Annona senegalensis*	j

There were ten species of trees identified in twelve farms, where the Swahili, common, binomial, and assigned names of the identified trees for this study are listed on Table 4.1.. The findings of number of trees of different age per farm based on physical counting in the studied area is listed in Table C.2. in Appendix C. The average number of trees categorised by their species and approximate age are shown in Figure 4.1 (refer to Table 4.1. for the assigned names). As seen in Figure 4.1., the most common tree species identified were *Azadirachta indica* and *Casuarina equisetifolia* with average of 13 trees and 10 trees of 3-6 years old grown in each farm, respectively. Similarly, *A. indica* and *C. equisetifolie* had an average of 16 trees and 3 trees over 6 years old, respectively. The number of young *A. Indica* and *C. equisetifolie* planted less than three years old were 17 trees and 10 trees, respectively, which shows the potential amount of woody biomass within the next several years might potentially increase. Overall, the average number of trees per farm identified in Waa Ward, Kwale County were 7 trees, 5 trees, and 4 trees based on their approximate age of 0-3 years, 3-6 years, and over 6 years, respectively.

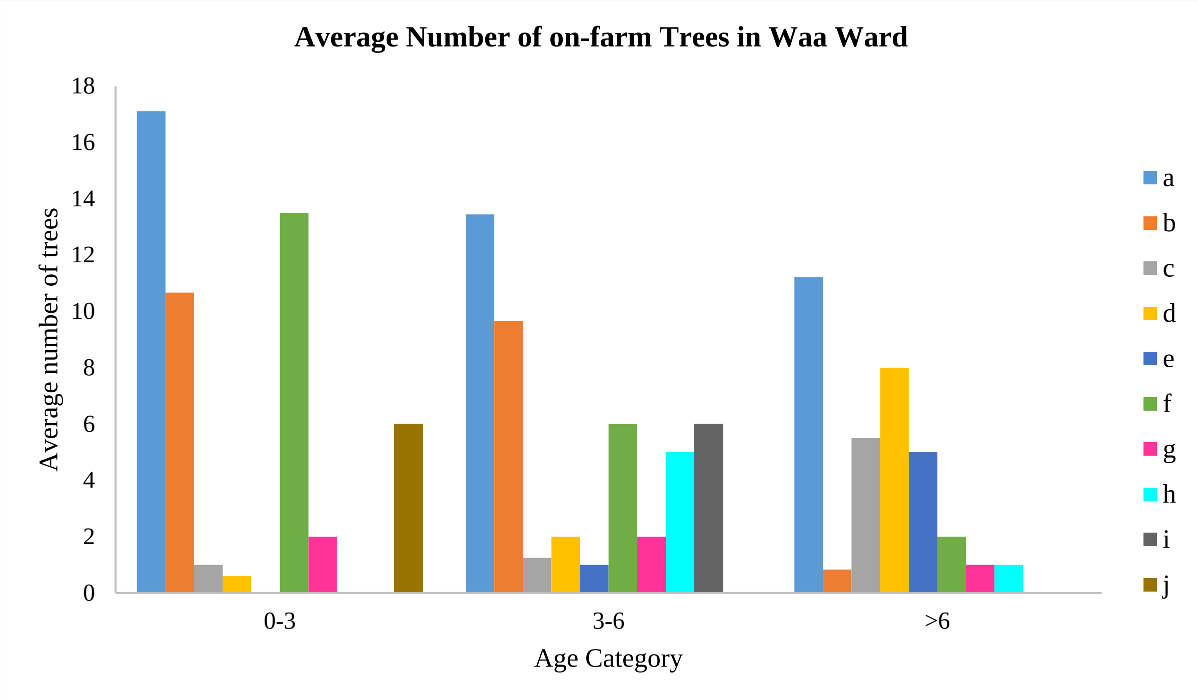

Figure 4. 1. *Average number of on-farm trees identified in twelve farms during biomass measurement in Waa Ward, Kwale County*

Table 4. 2. *Species of trees and their respective average weight of prunings (kg/tree/year)*

Assigned name for this study	Average weight of pruning (kg/tree)			
	3-6 y.o.	Notes	>6 y.o.	Notes
a	40.3	Based on average weight during field study	40.3	Based on assumption that the average weight is similar to the younger trees
b	15.0[1]	Midgley and Sylvester (2016)	28.4[a]	Gupta and Gupta (2014), p. 173.
c	N/A	Pruning started later than the other species.	58.0	Balamohan et al. (2014)[1]
d	N/A	Pruning started on year 4	76.7	Based on average weight during field study
e	0.000	Not enough information	18.0	Based on average weight during field study
f	23.5	Based on average weight during field study	0.00	Not enough information
g	27.0	Based on average weight during field study	22.5[1]	Zolha (2016)
h	0.000	Not enough information	0.000	Not enough information
i	75.0	Based on average weight during field study	0.000	Not enough information
j	0.000	Not enough information	0.000	Not enough information

[a] The data is taken from the referred literature (see the notes section)

Depending on the age of tree, the weight of pruned biomass was highly varied. For instance, the weight of prunings of *A.indica* of age range of 3-6 years old varied from 21.0 kg to 115 kg per tree, with an average of 40.3 kg per tree. While, the average weight of pruning *C. equisetifolie* of the same range of age, 3-6 years old, was 15 kg per tree as determined from literature review, due to lack of data. From the questionnaire answered by the farmers, pruning branches was normally performed once a year before planting season to trees that were three years and older, hence, only trees age three years old and above were considered in this study. Table 4.2. lists the average weight of pruned branches from different species of tree, obtained from various sources including the observation results and literature data. The data of weight average was used to determine the on-farm woody biomass availability.

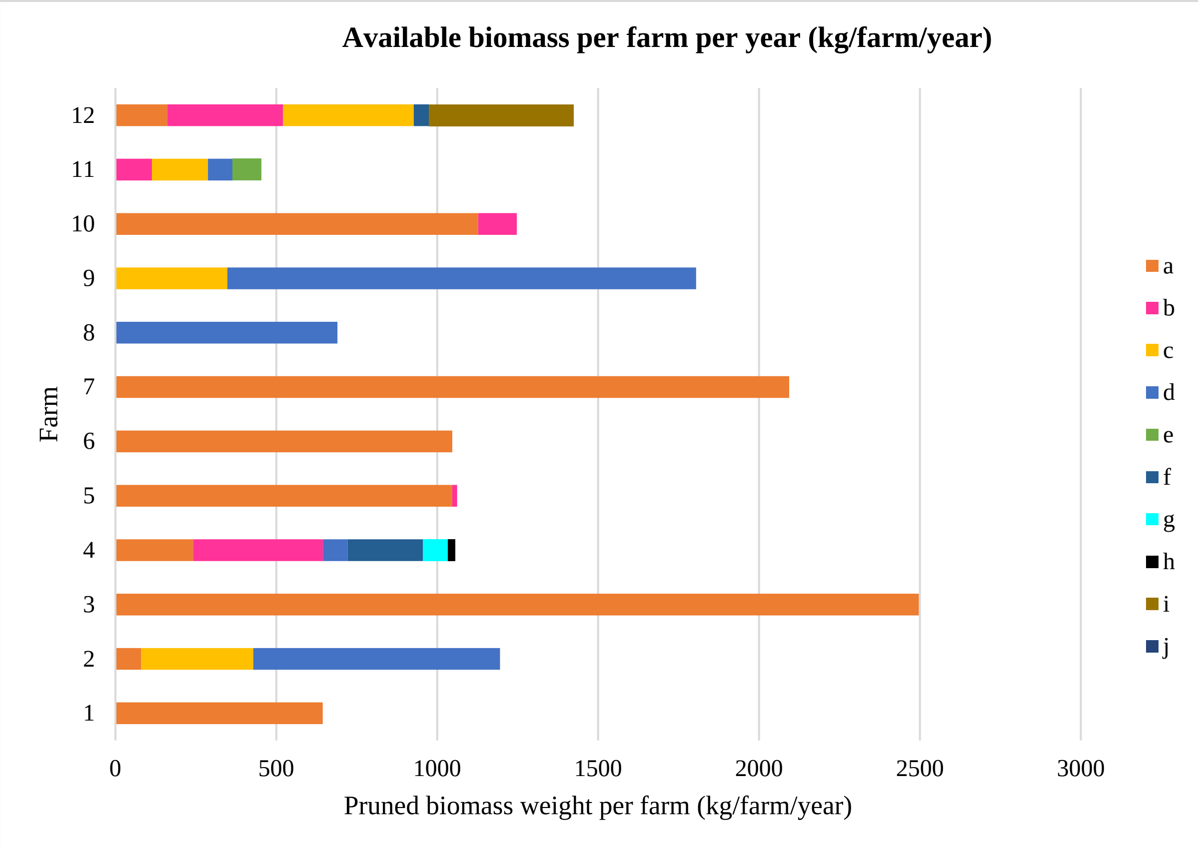

Figure 4. 2. *Available on-farm woody biomass per farm per year at Waa Ward, Kwale County, Kenya*

Based on the average weight of wet biomass divided by the area of the farm, the total quantity of potential pruned biomass per unit area (kg/ha) in each farm was determined, in addition to the potential pruned biomass per farm. It is important to note the time unit for the biomass availability is per year, as pruning was normally done annually. Figure 4.2. and 4.3. shows the total quantity of potential pruned biomass variations in twelve participated farms in Kwale County, Kenya. The lowest and highest weight of biomass that a farm could obtain were 0 kg/farm and 2497 kg/farm, respectively, by pruning *A. indica* older than 3 years old (refer to Figure 4.2). While, the lowest and highest weight of pruning *C. equisetifolie* of the same age range were 0 kg/farm and 403.4 kg/farm, respectively (refer to Figure 4.2). *A. indica* and *C. equisetifolie* were not grown in some farms, hence the lowest weight of pruning the two species were shown to be 0 kg in these farms. Irrespective of species the average amount of prunings a farmer had 833.4 kg per year of woody biomass obtained from pruning.

Figure 4.3. illustrates the biomass availability on the farms in terms of unit of area. For instance, the lowest and highest weight of available biomass could be obtained were 0 kg/ha and 1664 kg/ha, also by pruning *A. indica* of 3 years old and older (refer to Figure 4.3). While the lowest and highest available biomass by pruning *C. equisetifolie* of 3 years old and older were 0 kg/ha and 269 kg/ha (refer to Figure 4.3). Table 4.3 summarises the average woody biomass availability regardless of age and species on the farms at Waa Ward, Kwale County.

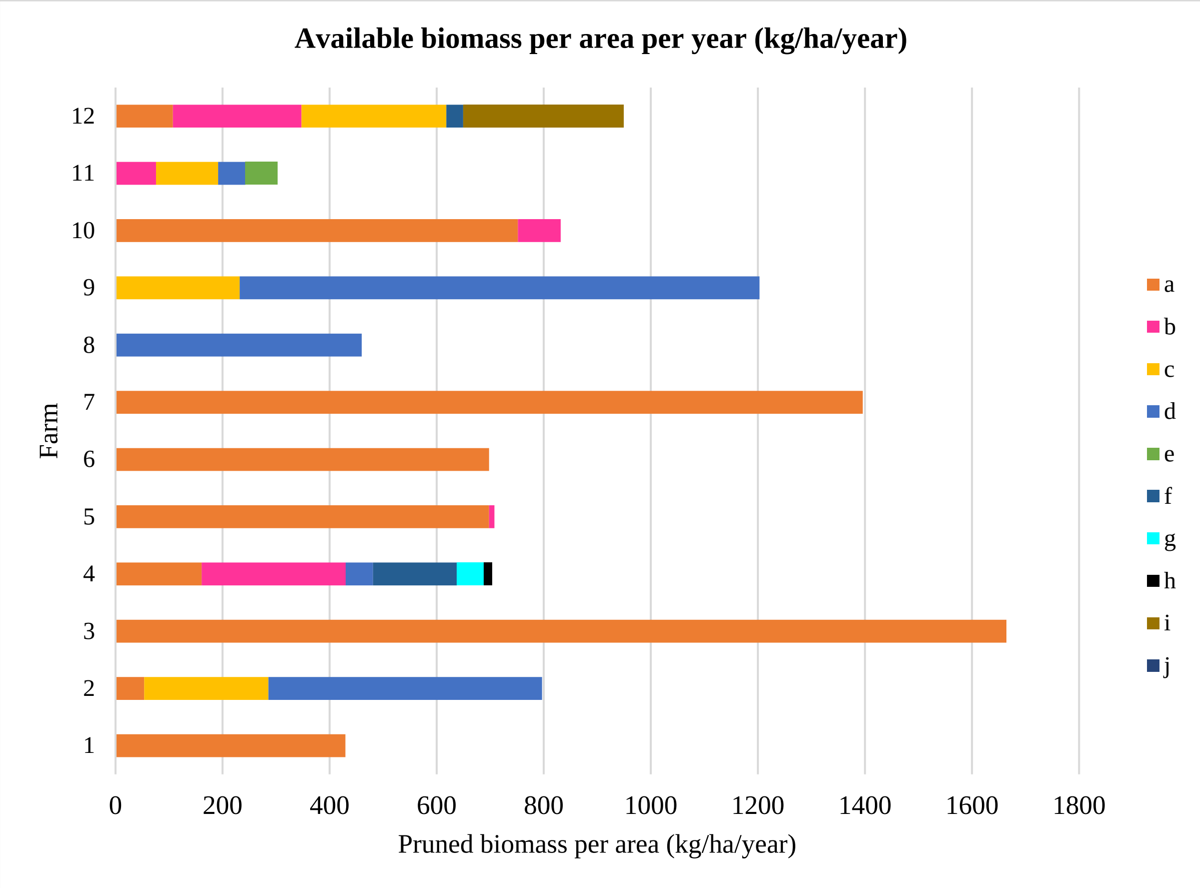

Figure 4. 3. *Available woody biomass per area per year on farms at Kwale County, Kenya (kg/ha/year)*

Table 4. 3. *Woody biomass availability on the farms at Waa Ward, Kwale County*

Biomass availability	Average	SD[a]	Maximum	Minimum
kg/farm/year	1268	605	2497	454
kg/ha/year	845	404	1664	303
kg/capita/year	283	165	624	107
kg/capita/day	0.775	0.453	1.72	0.295

[a]Standard Deviation

4.1.2. Energy availability for cooking

Based on the questionnaire, almost all the households observed currently used woody biomass as their primary source of cooking energy, hence, the assumption of 'no competing use of woody biomass' was correct. A small portion of the pruned wood would be used for other purpose, i.e. house construction, as well from time to time. In the study, the competing use of pruned woody biomass was not included in the calculation due to its small percentage of used. The energy availability per unit farm for each species of trees grown in the observed farms are shown in Figure 4.4. The Lower Heating Value (LHV) for each species of tree to calculate the energy availability was obtained from the field test and literatures (see Appendix B).

The energy availability for cooking depends on the biomass availability in the observed farms. However, both biomass and energy availabilities did not depend on the area of the farms. For instance, farm 3 had the highest availability of energy from *A. indica* tree, 1664 GJ/year or approximately 4.56 GJ/day, while it was also one of the smallest farm with only one hectare of area. In the meantime, farm 5 had the largest area of four hectares, with the energy availability much lesser than farm 3, 8.72 GJ/ha/year or approximately 0.023 GJ/ha/day from growing 98% of *A. indica* in the farm. There were two species that were not available as energy yet due to their young age, namely *Annona muricata* and *Annona senegalensis*. The average of total energy availability on observed farm households and the average energy availability according to different species at observed farms are shown in Table 4.4.

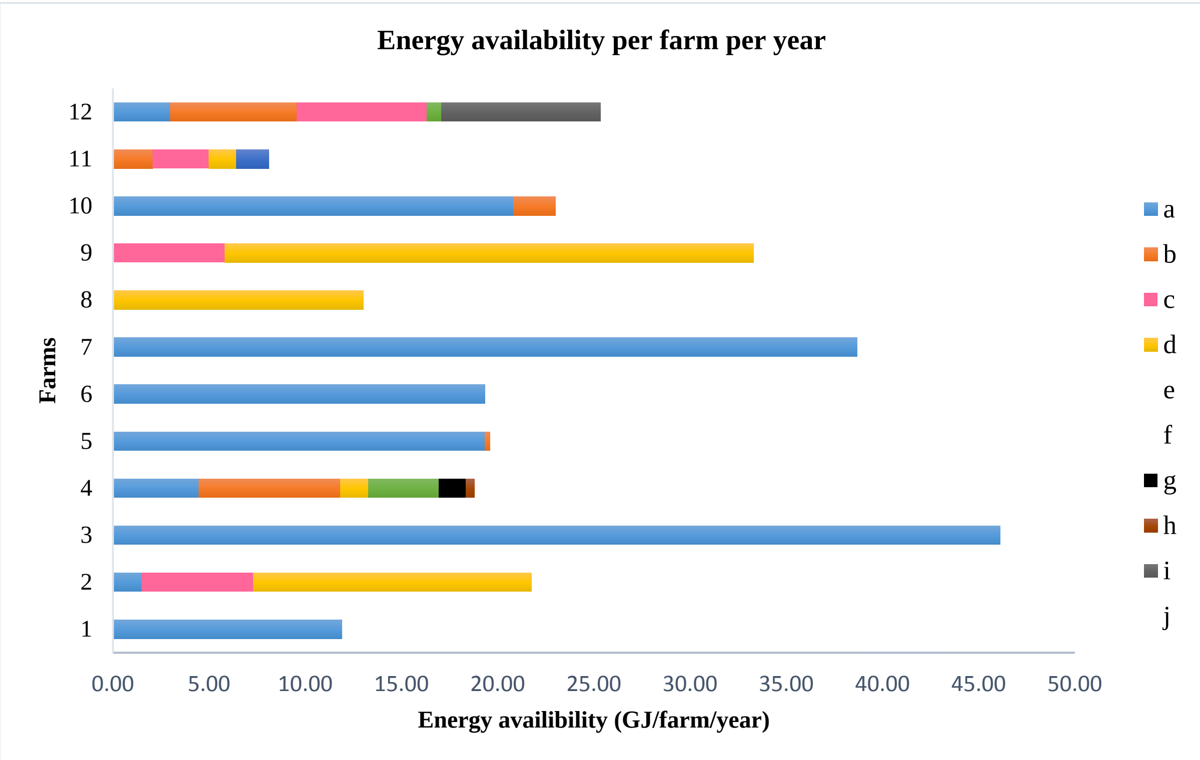

Figure 4. 4. *Energy availability on the farms determined from tree species in Waa Ward, Kwale County. The assigned names of species of trees in Figure 4.4 can be referred to Table 4.1.*

Table 4. 4. *Energy availability on twelve farms in Waa Ward, Kwale*

Energy availability	Average	SD[a]	Maximum	Minimum
GJ/farm/year	23.3	11.2	46.1	8.10
GJ/ha/year	16.1	7.08	30.7	5.40
GJ/capita/year	5.18	3.03	11.5	1.98
MJ/capita/day	14.2	8.31	31.6	5.43

[a]Standard Deviation

4.1.3. Household fuel and energy consumption

Wood fuel consumption in Kwale, Kenya, varied between farm depending on the woody biomass species and availability, type of dishes cooked during uncontrolled Kitchen Performance Test (KPT) and most importantly type of cookstove used for cooking. The Kenyans' staple foods, ugali and sukuma wiki, were commonly cooked by the observed houses in Waa Ward. Although not always cooked in combination, ugali was observed to be cooked in 6 households during the observation. The combination of cooking ugali and sukuma wiki for a meal was observed in two households. While the other four households combined ugali with other type of dishes, mostly stews. The rests of the observed households cooked variant type of dishes including beans, mandazi, chapatti, and tea. Cooking tea in this case was boiling the water to make tea, due to the nature of tradition in the area not putting in the tea leaves while the water was boiling.

Table 4. 5. *The overall performance, determined by the average value, of cooking with traditional three-stone open fire and improved cookstove, TLUD gasifier.*

Parameter	Unit	3 Stone Fire		TLUD Gasifier	
		Average	SD[a]	Average	SD[a]
Number of households observed		4		12	
Amount of dishes cooked for dinner meal		2		2	
Frequency of using cookstove per day		2		1	
Household size	capita	6	1	5	2
Total time for cooking	min	0:49	0:26	0:51	0:17
Total time for cooking without changeover	min	-	-	0:50	0:14
Time to ignite fire	min	0:04	0:02	0:14	0:05
Net fuel consumption to cook a dinner meal	kg	1.83	0.25	1.08	0.35
Net fuel consumption per meal per person	kg/capita	0.32	0.23	0.21	0.07
Thermal efficiency	%	8.75%	3.27%	17.67%	8.33%
Net energy consumption per meal per person	MJ/capita	5.78	1.32	4.15	2.70
Net energy delivered	MJ/capita	0.46	0.10	0.71	0.63

[a]Standard deviation

Out of 12 households observed during the KPT, 6 houses used *A. indica*, 5 houses used *C. equisetilofia*, and 1 used *Melia azaderach* for cooking. Based on the interview with the main cooks in different households, *A. indica* and *C. equisetilofia* were the most preferred species of trees for cooking fuel. Appendix C.1. shows the results of KPT from each observed household, while Table 4.5. lists the average value from KPT. To determine the parameters per capita, the observation results from household basis was divided by the total amount of people in the household. The resulting energy consumption per capita served as functional unit in Life Cycle Assessment (LCA) to determine the climate change impacts of traditional and improved cooking techniques.

Wood energy consumption in Waa Ward varied between farms. Energy and fuel consumption were higher when using traditional cooking method compared to improved cooking method with 1.83 kg per capita per meal and 5.78 MJ per capita per meal (refer to Table 4.5). Likewise, use of improved cooking method reduced wood energy and fuel consumption per capita per meal by 28% and 41% respectively (refer to Table 4.5.). As can be seen from Table 4.5., except the total time for cooking and time to ignite fire, the performance of Gastov for cooking was better than three-stone open fire. Time for cooking was considered when the first dish was started to be cooked until the last dish were finished cooking. Changeover time is time required when refilling the canister of Gastov with fuel when the cooking is not finished yet, in order to be able to finish cooking the meal. In particular, the thermal efficiency of TLUD gasifier was twice more efficient than the three-stone open fire. Since the net energy delivered is directly affected by thermal efficiency, the average net energy delivered by TLUD gasifier was larger than the three-stone open fire.

4.1.4. Availability and need of fuel and energy

A comparison of fuel and energy availability and needed per household is presented in Table 4.6. The average values used to compare were obtained from biomass measurement and KPT (see Chapter 4.1.1 to Chapter 4.1.3). Gross fuel and energy required for cooking were used to compare with the availability of biomass and energy on the farms regardless of the species of woody biomass used for cooking during the KPT. Gross fuel consumption was estimated by using the value of fuel consumption before subtracted with the char produced. The fuel and energy required for cooking per day were estimated by assuming that fuel and energy used for cooking breakfast and lunch were the same with fuel and energy required for cooking a dinner meal.

Table 4. 6. *A comparison between fuel and energy availability with the fuel and energy required for cooking per day*

Parameter	Unit	Availability	Need	
			Three-stone	TLUD gasifier
Fuel (mass)	kg/household/day	3.47±1.66	5.48±0.877	3.09±1.22
Energy	MJ/household/day	63.7±30.7	96.8±21.0	55.7±22.4

The results in Table 4.6. show that in average the wood fuel and energy availability within farms could not meet the needs of cooking with the traditional three-stone open fire. Cooking with traditional three-stone open fire everyday could lead to deficiency in some households. An average estimation of 36% and 34% of biomass deficiency on the farms would be most likely developed by following the traditional cooking practice. In contrast, cooking with the improved cookstove three times a day reduced the amount of required fuel and energy for cooking, and thus, could make up the energy deficiency on the farms. In conservative estimation, using TLUD gasifier could cause surplus fuel and energy availability on the farms by 12% and 14% on average, respectively (Table 4.6).

4.2 Life Cycle Assessment

This section presents the results from the life cycle impact assessment (LCIA) of biochar system in Waa Ward, Kwale, and the sensitivity analysis for selected parameters. The results are divided into two parts based on the usage of cooking technique during observation. The first part is a comparative assessment, comparing reference and improved systems, while the second part is a stand-alone assessment, assessing the improved system in different households. Both assessments used the same functional unit, system boundary, and assumptions.

4.2.1 Life Cycle Inventory

This section presents the system inventory obtained from the fieldwork and categorised by the two systems, reference and improved systems, and the modules, feedstock and cooking modules. The inventory for soil module is disclosed in the Chapter 3.3 since it was not obtained through fieldwork but calculations from the existing data as well as other literature data in Chapter 3.

Feedstock module

The data for this module consists of several parameters, including availability of on-farm woody biomass through prunings, fuel consumption, and fuel characteristics and are listed in Table 4.8. To be more specific, the data of the available on-farm biomass were obtained during biomass measurement, while the rest of the data were obtained from KPT, interview and literatures. The data obtained from KPT for feedstock module included fuel consumption and moisture content. While the LHV values were estimated by allocating moisture content values obtained during KPT to the equation in Appendix B.1.

Cooking module

The data for this module presented here consists of the performance of the two cooking practices including thermal efficiency, conversion efficiency and the number of dishes cooked for a dinner meal in each household during KPT (Table 4.7). While thermal efficiency is a performance measurement for both cookstoves, conversion efficiency of TLUD gasifier defined as the ratio between the useful output (char) and the input (fuelwood).

Table 4. 7. *Inventory data for cooking module obtained during fieldwork*

	Fuelwood	# Dish cooked	Three-stone open fire	TLUD gasifier	
			Thermal efficiency (%)	Thermal efficiency (%)	Conversion efficiency (%)
Household 1	*C.equisetifolia*	2	8	21	23
Household 2	*A. indica*	3	10	13	28
Household 3	*C.equisetifolia*	3		8	22
Household 4	*M. azedarach*	2	13	21	17
Household 5	*C.equisetifolia*	2		13	23
Household 6	*C.equisetifolia*	2		19	20
Household 7	*A. indica*	2	4	15	30
Household 8	*A. indica*	3		20	70
Household 9	*A. indica*	3		12	32
Household 10	*C.equisetifolia*	2		16	26
Household 11	*A. indica*	2		42	28
Household 12	*A. indica*	2		12	31

Table 4. 8. *Inventory data for feedstock module obtained during fieldwork. Moisture and carbon contents were obtained from literature.*

	Feedstock (firewood)	Renewability (%)	Availability on-farm (kg/capita/day)	Frequency used per day		Net fuel consumption (kg/capita/meal)		Moisture content (%)	Carbon content (%)	LHV (MJ/kg)
				3-S open fire	TLUD	3-S open fire	TLUD			
Household 1	*C.equisetifolia*	100%	0.20	2	1	0.36	0.15	14.5	72.0	18.4
Household 2	*A. indica*	100%	0.31	1	2	0.29	0.25	16.0	70.9	18.2
Household 3	*C.equisetifolia*	100%	1.14	2	1	-	0.51	15.2	72.0	18.4
Household 4	*M. azedarach*	100%	0.32	2	1	0.50	0.18	17.6	70.9	15.6
Household 5	*C.equisetifolia*	25%	0.32	2	1	-	0.11	18.5	72.0	18.3
Household 6	*C.equisetifolia*	0%	0.32	1	2	-	0.25	17.4	72.0	18.3
Htousehold 7	*A. indica*	100%	0.96	2	1	0.83	0.12	20.7	70.9	18.1
Household 8	*A. indica*	100%	0.42	2	1	-	0.08	13.9	70.9	18.2
Household 9	*A. indica*	100%	0.55	2	1	-	0.5	17.6	70.9	18.8
Household 10	*C.equisetifolia*	0%	0.38	1	2	-	0.12	17.4	72.0	18.3
Household 11	*A. indica*	100%	0.41	1	2	-	0.33	13.9	70.9	19.2
Household 12	*A. indica*	100%	0.59	2	1	-	0.27	17.6	70.9	15.6

4.2.2 Comparative assessment: reference vs improved systems

In the fieldwork, four out of twelve participating households were decided to perform the KPT using both cooking techniques in order to compare the climate change impacts caused by each cooking technique. Figure 4.6 summarises the comparative LCA of reference and improved system in Kwale. Based on the assessment of four participant households, it can be seen from the graph that in all participant households, the improved systems were better in term of climate impact than the reference systems. In Figure 4.5, the climate change impact was calculated using 100-year time frame and Set 2 of pollutant. Set 2 of pollutant was chosen to capture more accurate estimation of climate change impacts of the two systems. In all four households, it can be seen that by using the improved cookstove for cooking, calculated GHG emission was negative, where GHG reductions happened. The most visible difference in terms of comparing climate change impacts of the two systems was found in Household 7, with GHG reduction of 0.440 kgCO_2-eq when cooking using Gastov.

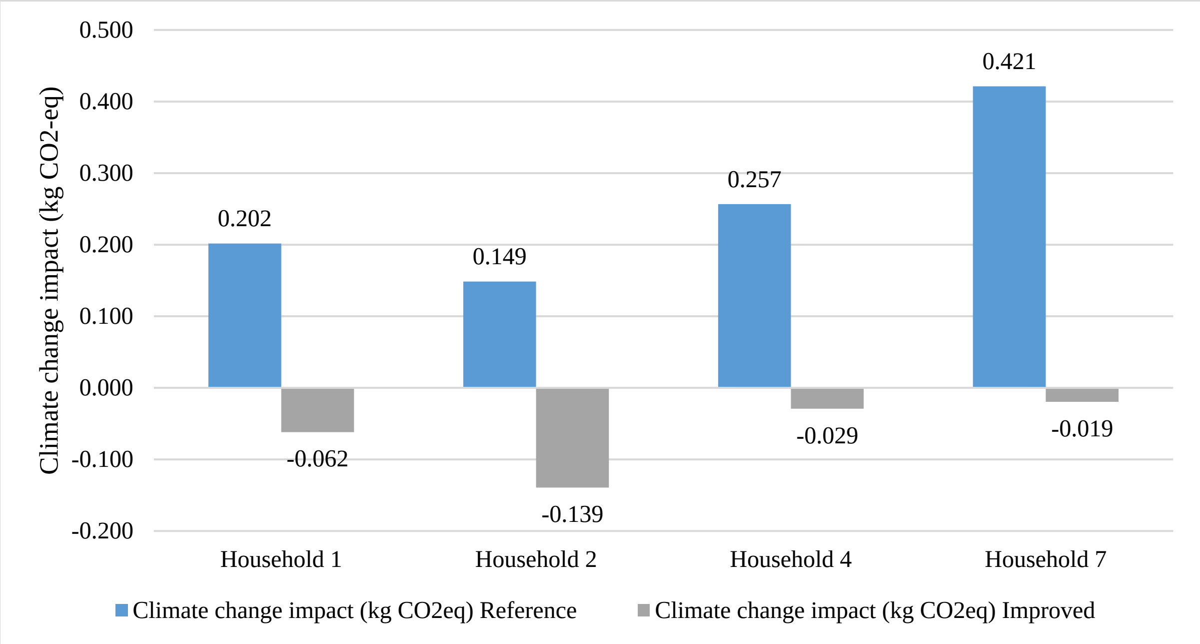

Figure 4. 5. *Results for comparative LCA of four participant households. Climate change impact per functional unit was determined by 100-year time frame and Set 2 pollutant. Functional unit: net energy consumption per capita per meal*

Since the climate change impacts of the two systems in Figure 4.5. were estimated using 100-years of time frame and Set 2 of pollutants as default, therefore investigating whether the climate change impacts changed due to different time frame and sets of pollutants was essential. The climate change impacts altered when the time-frame and sets of pollutants were changed (Figure 4.6). Set 2 of pollutants led to a higher climate change impact than Set 1, regardless the time frame. An intriguing fact of the estimated climate change impacts of the improved system led to negative climate change impact with any combination of time frames and sets of pollutants, aside from the combination of 20-year impact (GWP_{20}) and Set 2 which relatively weighed the credit from biochar the lowest (Figure 4.6). The significance of interpretation of climate change impacts on different time frame and pollutant set depends on the latter use and goal of the LCA. For example, if the results are used for policy recommendation, the performance of each system changes in absolute is less important, instead how the relationships between the systems are affected is more significant. The GWC savings from improved system are illustrated in Figure 4.7. Climate change mitigation in relation to the reference system can be seen in all households regardless of time frame and set of pollutant. In other words, the magnitude of the results are sensitive to changes in the assessment framework, while in any case the improved system is the best alternative in compare to the reference system.

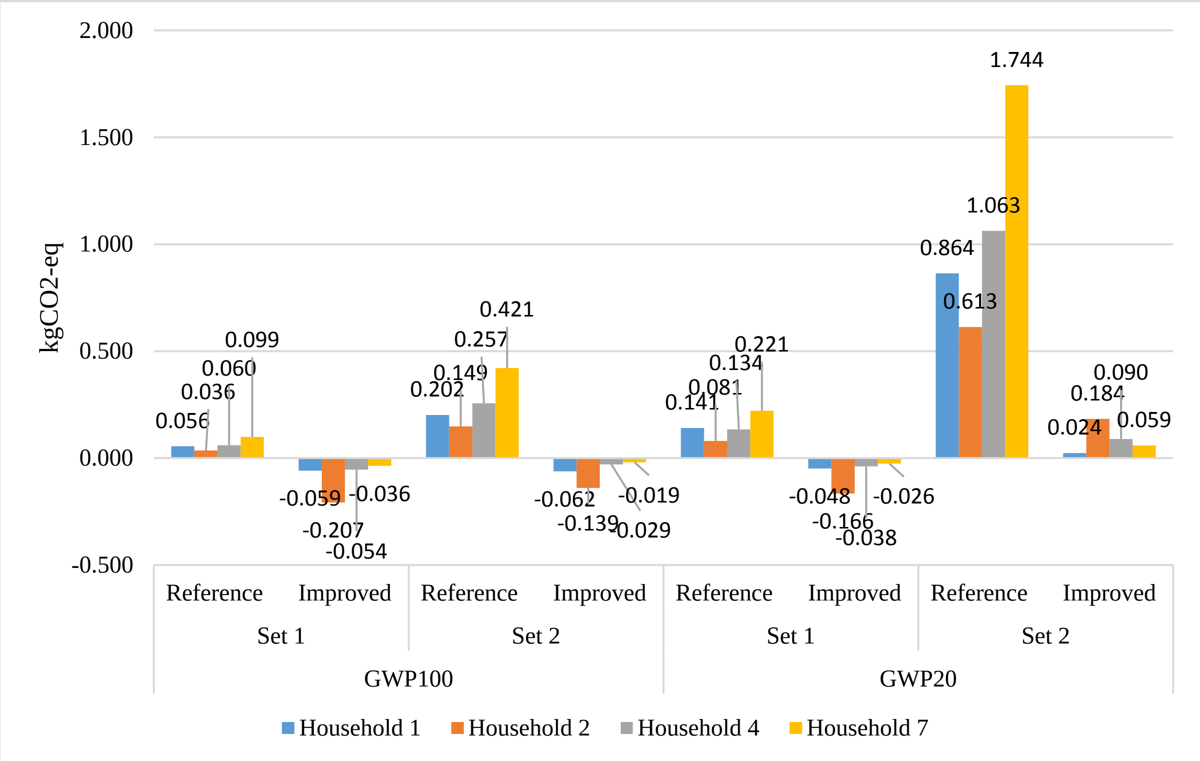

Figure 4. 6. *Climate change impacts per functional unit determined with different time frame and set of pollutants. Functional unit: net energy consumption per capita per meal*

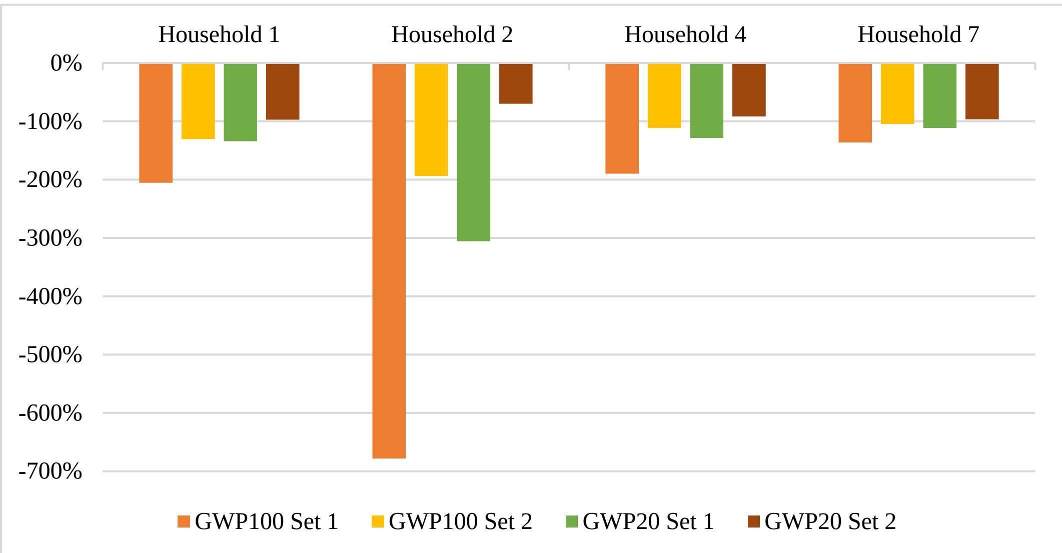

Figure 4. 7. *Climate change mitigation potential of the improved system in relation to the reference system in % GWC saved*

Figure 4.8. indicates that the majority of GHG emissions were from carbon dioxide, CO_2, investigated in both reference and improved systems. The contribution of pollutants as seen in Figure 4.8. was calculated with a combination of GWP_{100} and Set 2 of time frame and pollutants set, respectively. The second most critical pollutants under the reference system were carbon monoxide and black carbon, CO and BC, respectively, where they indicated that improving thermal efficiency would lower the fuel consumption, and thus, reduce these pollutants directly resulted by net energy consumption. Under the improved system, where the thermal efficiencies were higher, CO and BC were significantly lower. In addition to the major GHG emission pollutant, Figure 4.8. also indicates the majority of GHG reductions of both reference and improved systems were also from CO_2, found as RB-credit. RB-credit is the credit for renewable biomass accounts for CO_2 uptake during feedstock regrowth. The second GHG pollutant reducer was biochar credit, where the contribution of it could only be found under the improved system since biochar was produced by the improved cookstove, TLUD gasifier.

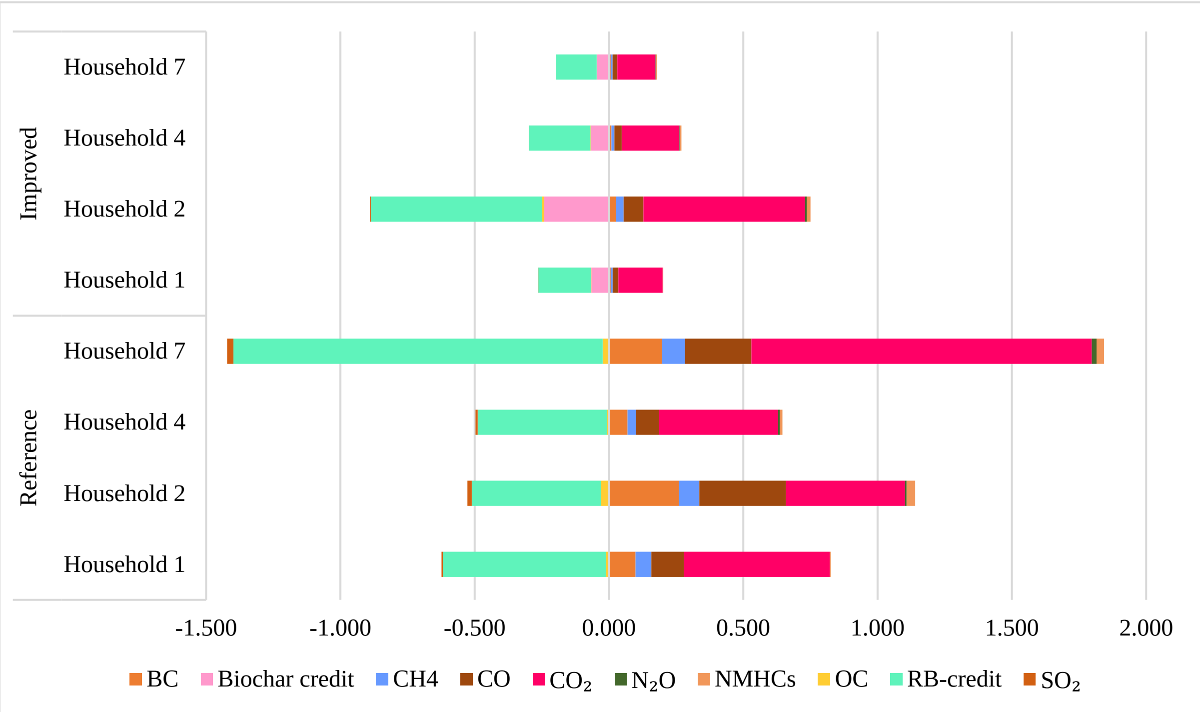

Figure 4. 8. *Contribution analysis of pollutants, estimated with GWP100 and Set 2 of time frame and pollutants set, respectively*

4.2.3 Stand-alone assessment: improved system

There were twelve households participating in the improved system observation. In this case, eight households did not participate in cooking with the traditional three-stone open fire. Figure 4.9. depicts the climate change impacts of the improved systems and were determined by using GWP_{100} and Set 2 of pollutants based on the functional unit, net energy consumption per capita per meal. The extended set of pollutants was selected to better estimate the climate impacts in the improved system. The highest climate change impact was found in household 6, while the lowest was found in household 9. It was investigated that there were two households, household 6 and 10, which did not regrow the type of fuelwood used during the observation, or fNRB of 100%, and thus leading to the high climate change impacts and no GWC savings.

Among all the participant households, it was found that there were two species of fuelwood used during the observation, namely *A. indica* and *C. equisetifolia*, or commonly known as neem tree and casuarina tree, respectively. Based on the overall performance, neem tree was a better option to use as a feedstock (Figure 4.10). Due to 100% chance of regrowing the neem tree, or 0% of fNRB, the average climate change impacts caused by using the neem tree as a feedstock was -0.180 kg CO_2-eq. The credit of renewable biomass accounts for CO_2 during feedstock regrowth, and thus 0% of fNRB led to lower climate change impact. The use of casuarina tree for feedstock was not an ideal option in Waa Ward, Kwale County, due to higher fNRB. This was concluded based on the trend amongst the farmers in Kwale where after casuarina trees reach their maturity, they will be cut and sold as timber in the market. In some households, the farmers would replant casuarina trees but in some would not, depending on their economical situation. Based on interviews with some farmers that prefer not to replant casuarina trees unless necessary, selling timber from a mature casuarina tree worth of 500 Kenyan Shillings (5 USD). In contrast, neem tree has more benefits than casuarina tree, e.g. as medicine and its timber has higher selling price on the market. Besides that, using neem tree as a feedstock led to higher thermal efficiency of the TLUD gasifier and consumed less energy.

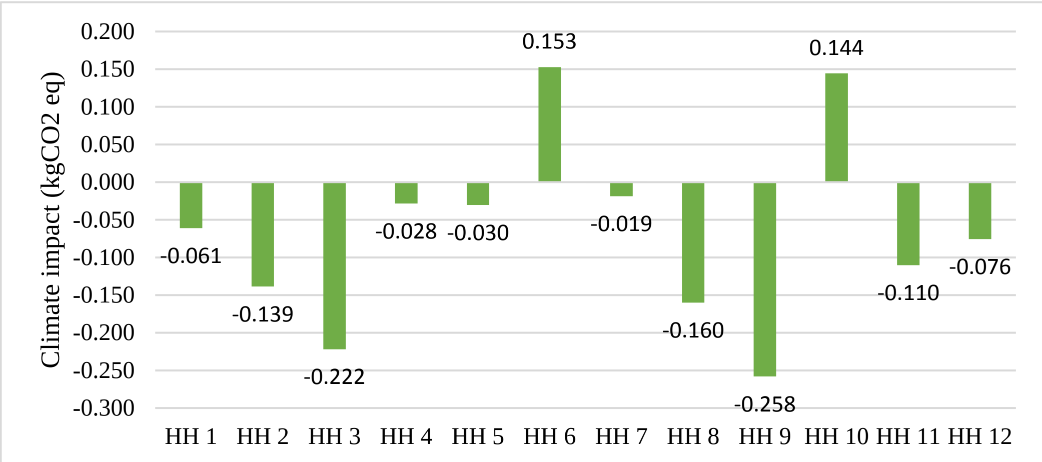

Figure 4. 9. *Climate impacts per functional unit (kgCO2-eq) of The Gastov assessed at twelve households using GWP100 and Set 2. Functional unit: net energy consumption per capita per meal (HH:household)*

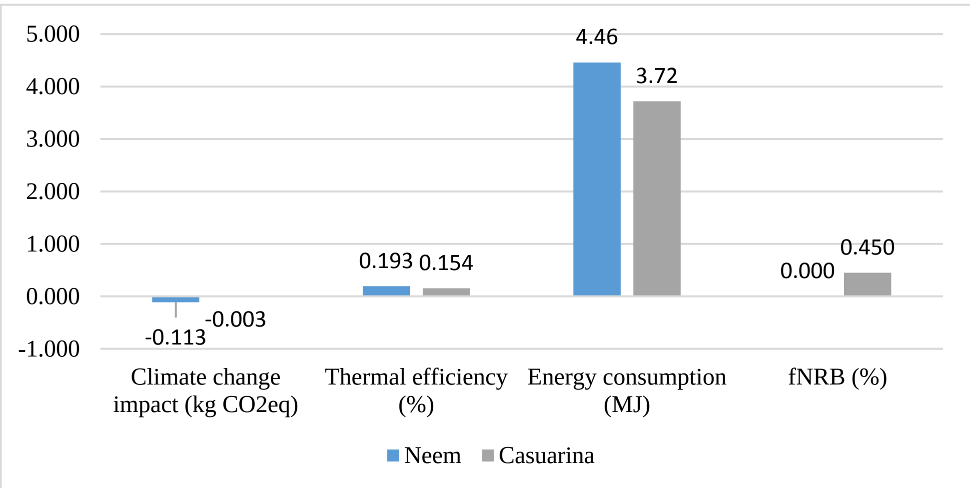

Figure 4. 10*. Comparison of improved system performance according to the species of fuelwood, determined with GWP100 and Set 2 of pollutants.*

Looking at the pollutant contribution in Figure 4.11, the majority of both the GHG emissions and reductions investigated in all twelve participant households were from CO_2, with much smaller contributions from CO. The lowest contributor of CO_2 was found in household 8. As previously discussed, the renewable biomass credit (RB-credit) reported the uptake of CO_2 during feedstock regrowth, while the biochar credit accounted for carbon sequestered in the biochar system. The stable carbon in biochar caused a negative GWC in almost all participant households, and therefore caused the negative net of GWC in the respective participant households (Figure 4.11).

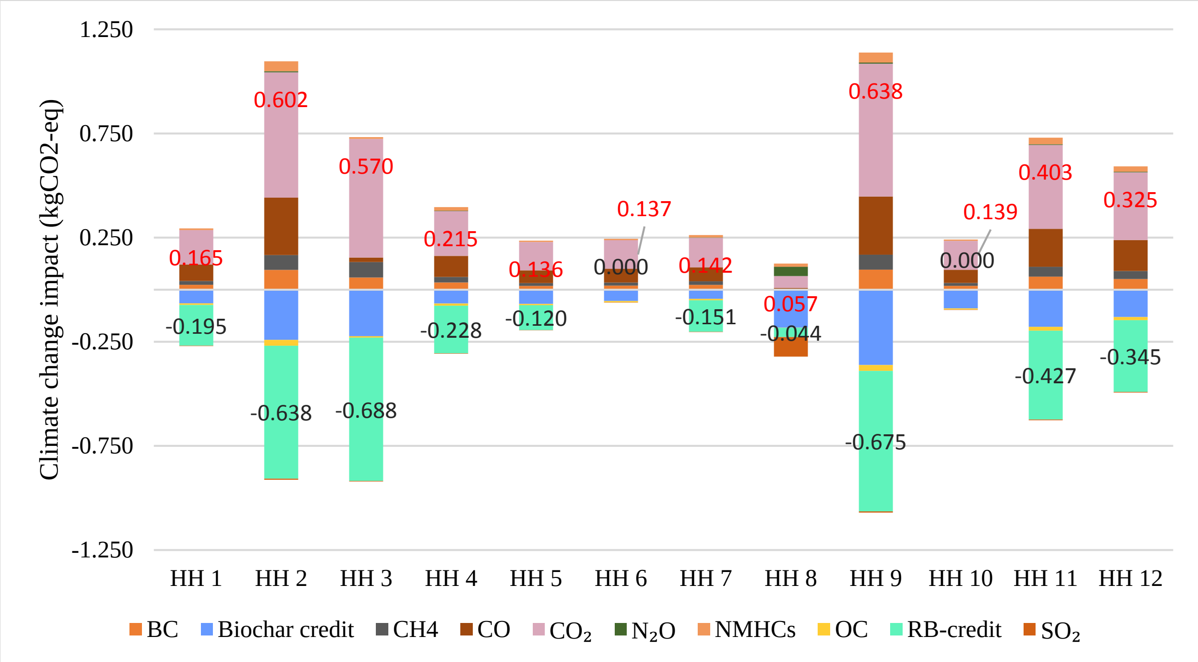

Figure 4. 11. *Contribution analysis of pollutants emitted in improved system, estimated with GWP20 and Set 2 of time frame and pollutants set, respectively.*

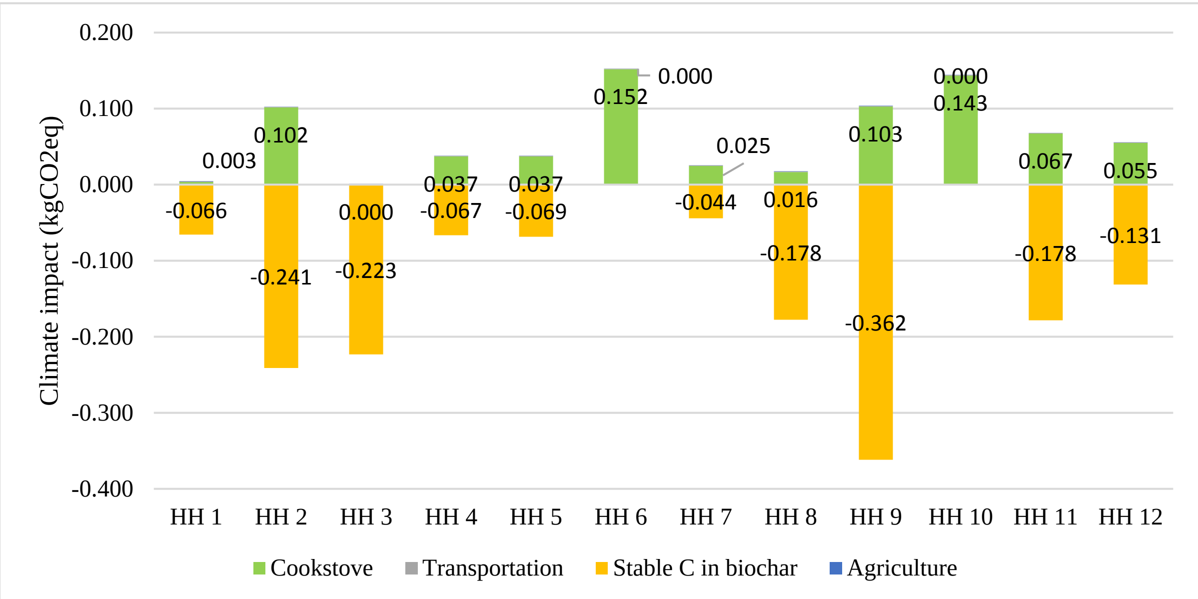

Figure 4. 12. *Emission contributions of different activities under the improved system, determined by using GWP100 and Set 2*

Lastly, the contribution analysis based on activities performed under the improved system is shown in Figure 4.12. Cooking activities is the largest GWC contributor in almost all the twelve households, while stable C in biochar is shown to be the largest GWC saving (Figure 4.12). Finally, the transportation is shown to a very insignificant portion of overall emissions in all twelve households (Figure 4.12).

4.2.4 Sensitivity Analysis

Sensitivity analysis was conducted in order to evaluate the variability in the results of LCA as a function by varying key input parameters. In this study, the sensitivity analysis was individually performed on the four households participated in the comparative assessment. The aim of the sensitivity analysis was still to compare the performance of reference and improved systems under alternating input parameters. The input parameters that were investigated were the fraction of recalcitrant carbon in the biochar and the fraction of non-renewable biomass (fNRB). The sensitivity analysis input parameters are listed in Table 4.9.

Table 4. 9. *Sensitivity analysis input parameters*

Parameter	**Reference**	**Improved**	**Sensitivity range**
Stable carbon content of biochar (%)	0	80	0 – 90
Fraction of non-renewable biomass	0	0	0 - 1.0

Recalcitrant carbon in the biochar

The stable carbon content was varied in the range of 0 – 90% with input parameter in the improved system of 80%. The sensitivity analysis excluded the emission caused by transportation and used Kyoto Pollutants, Set 1, and 100-year time frame, GWP_{100}. Longer time frame was selected due to the nature of long-term effect of biochar. Further, the fNRB used for the sensitivity was set at 0% for all households analysed.

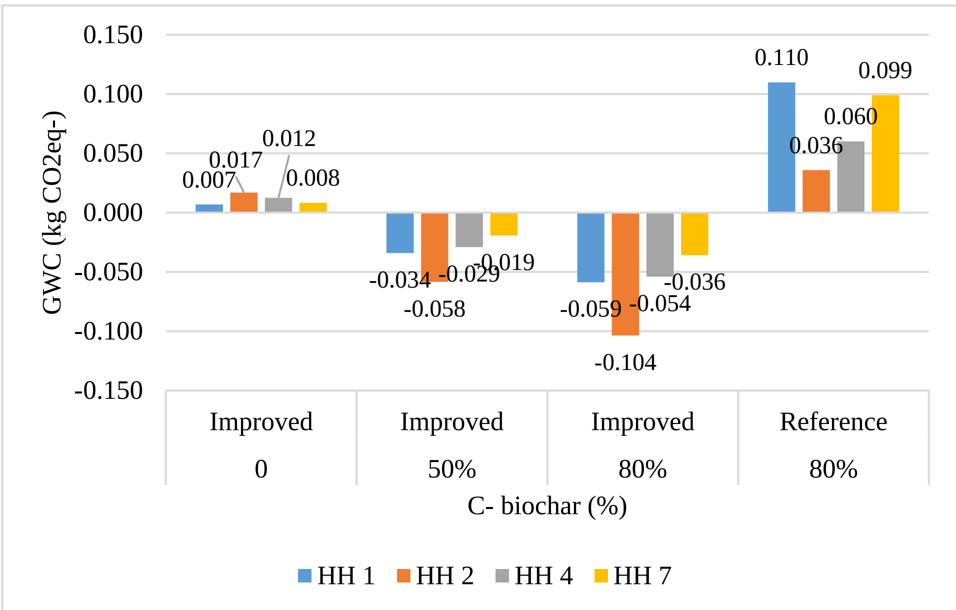

Figure 4. 13. *GWC of sensitivity results for stable carbon content of biochar parameter (kg CO2-eq), calculated using GWP100 and Set 1 of pollutants. Functional unit: net energy consumption per capita per meal*

The average changes in the stable fraction of carbon in biochar investigated in four participant households had big impacts. Figure 4.13 shows the estimated GWC (kg CO_2eq) in different stable carbon content scenario. A change in the stable carbon fraction in biochar from the LCA model of 80% input to 50% increases GWC by 44% in average (Table 4.10). In the meantime, a 90% stable carbon fraction lowers GWC by 15% in average compared to the modelled input value of 80%. The sensitivity analysis shows that when the stable fraction of the carbon in the biochar was set at 0%, the GWC of all four participant households shown above zero, in the other words, no GHG reductions (Table 4.10). These findings demonstrate that the stable carbon content of the biochar was an important factor in the biochar system at Waa Ward, Kwale County.

Table 4. 10. *Change percentages of GWC when stable carbon content in biochar is altered from the improved system default value*

Change (%)	**0%**	**50%**	**80%**	**90%**
Household 1	112	42	0	-14
Household 2	116	44	0	-15
Household 4	123	46	0	-15
Household 7	123	46	0	-15
Average	**119**	**44**	**0**	**-15**

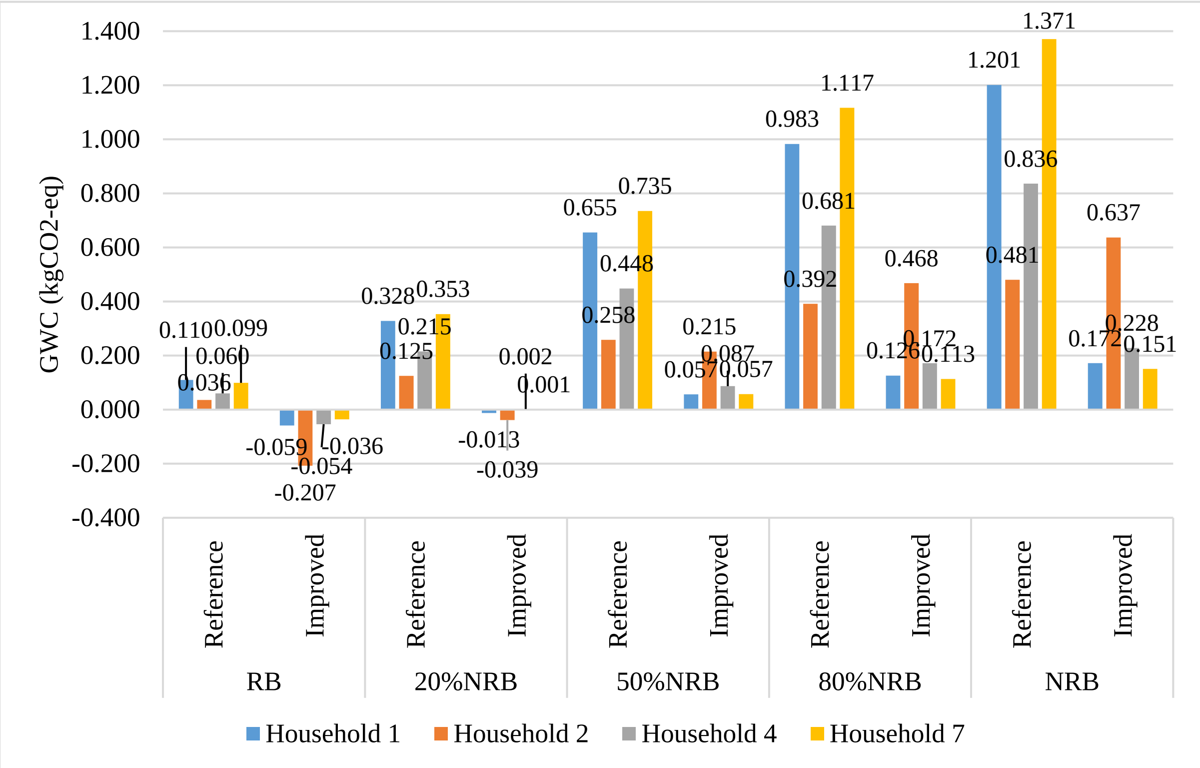

Figure 4. 14. *GWC of sensitivity results for fNRB (kg CO2-eq), calculated using set 1 and GWP100. Functional unit was net energy consumption per capita per meal.*

fNRB

The fraction of non-renewable biomass was altered from 0 to 1, with the base number of 0, as obtained from the field observation. The sensitivity analysis excluded the emission caused by transportation and used extended pollutant set, Set 1, and 100-year time frame, GWP_{100}. The stable carbon used for this analysis was 80%, as set in the LCA model. It is important to note that the species of woody biomass evaluated in this sensitivity analysis was the biomass used as feedstock for cooking during KPT. Figure 4.14. shows the GWC of four different changes of percentage of fNRB on the four analysed households.

When all of the biomass was assumed to be non-renewable, both in under reference and improved systems demonstrated a large increased of GWC (Figure 4.14). In particular under the improved system, when biomass is 100% non-renewable the GWC increased by more than 500% in average, as there would be no regrowth to uptake carbon dioxide emissions under this scenario. Even when the 50% of biomass is renewable, there are big increases seen in both reference and improved systems of 38% and 280% in average, respectively. Therefore, the fraction of non-renewable biomass was a major driver in GWC in Kwale, Kenya.

Chapter 5: Discussions

The findings reported in Chapter 4 suggest that the improved system is a better scenario and is also able to simultaneously provide energy security and climate change mitigation in the studied area, Waa Ward, Kwale County. This chapter discusses the findings as well as attempts to fulfil the aim of this study.

5.1. Findings from the Field

This section discusses the findings from the field Waa Ward, Kwale, including biomass availability, energy availability and kitchen performance test. Kitchen performance test (KPT) determined the energy consumption and delivered per capita per meal as well as the overall thermal efficiency of the cooking techniques, three-stone open fire and TLUD gasifier cookstove.

5.1.1. Biomass availability for bioenergy

The biomass observation suggests that in Waa Ward, Kwale, tree prunings was the most common technique to obtain fuelwood, while farm residues, i.e. twigs, dried leaves, were utilised when lighting the fire, as an animal fodder, or as an organic fertiliser. Pruning of trees is usually done for farm management, e.g. to clear the land, in addition for fulfilling the household energy requirement (Bilandzija, 2012; Jackson et al., 2000). Therefore, biomass availability for bioenergy was determined by omitting the other uses of the pruned biomass. Although, it genuinely depends on the farmers' intention of using all species of trees available on their farm as bioenergy. However, in this study all species of trees identified in the farm was assumed to be used for cooking energy.

The high variability of biomass availability in Waa Ward, Kwale, may be explained by different factors including the land size and economical condition of the farmer household. Size alone does not justify the unpredictability in the biomass production (Torres-Rojas et al., 2011). There were two other main factors affected the biomass availability and variability in addition to farm size as identified by Torres-Rojas et al. (2011), including farm age since conversion (i.e. deteriorating soil quality reduces productivity) and land allocation to specific crops (differences in annual yield determine total productivity). Moreover, farm age has also been identified as an important factor of biomass productivity by Whitman et al. (2010). In the study, farm age was included in the sensitivity analysis as a substitution for soil fertility, confirming that farm age is important for stocks of soil organic carbon (SOC) and yield. Particularly in Waa Ward, the size of household farms can be categorised as small farm, and thus, farmers normally make decisions based on the most efficient way to use the land (Scherr, 1995). This farm category assigns most of the land for cultivating crops, which assures food resources for the household (Torres-Rojas et al., 2011). All the household participants grow maize crops for different purposes some for selling at the local market, some for their own food resources, and the remaining is for animal fodder.

Firewood is the type of biomass commonly used in rural areas and sometimes in cities in Kenya as cooking fuel (Iiyama et al., 2014). Varied number of species used for cooking fuel was observed in the participating households. Some households grew more than one species of trees depending on various reasons, e.g. farm size, economical reason, occupation of head of the households, etc. Based on the biomass measurement, there were ten species of trees commonly used as fuelwood, with the most common used species are *A. indica (*neem) and *C. equisetifolia (*casuarina) tree species. Both tree species could be found on almost all the participant's farms. The on-farm tree counting during the biomass measurement was done by categorising the age of trees, to make the counting process easier. In average, 39% of the counted on-farm trees were younger than 3 years, 35% were within the range of 3 to 6 years, and the rests were above 6 years old. It was found that more than 17 neem trees in average (13% of average overall number of on-farm trees) were still younger than three years old, which means that the availability of biomass could be increased in the future. Regardless the fact that maize crop residues identified as the most productive bioenergy feedstock, trees were recognised as the second most productive biomass in Kenya (Torres-Rojas et al., 2011). Therefore, it was important for the farmers to grow trees in their farm despite the size of the farms and that the productivity of biomass could be explained by the age groups of land conversion from forest to agriculture as studied by Torres-Rojas, et al. (2011).

5.1.2. Household energy consumption and biomass selection for cooking

Wood consumption for cooking in Waa Ward varies between farms. Energy and fuel consumption were highest in households using traditional cooking method compared to improved cooking method per household per day in average, with 96.76 MJ and 5.477 kg, respectively (Table 4.6). Likewise, use of improved cooking method consumed lower energy and fuel per household per day in average, with 55.72 MJ and 3.086 kg, respectively (Table 4.6). Consequently, wood energy availability within farms is barely adequate to meet energy needs of the households using traditional three-stones open fire (Table 4.6), with the average available energy of 63.70 per household per day. This finding is consistent with the outcomes by Torres-Rojas (2011). Based on the assessment of four participant households, only three out of four of the participants could provide their daily cooking energy. The participant households can provide up to 65.83% of fuelwood necessity when cooking with the currently used cooking method, three-stone open fire. Which means that there are deficits of 34.17% of cooking energy availability in the household. This deficit energy can be reduced by using improved cooking method.

The performance of cooking method is evaluated by its thermal efficiency, cooking time and emissions. The study and development of improved cookstoves have been promoted in Kenya to decrease the quantity of fuel used for cooking, cooking time, and emissions as well as to improve the quality of rural livelihood (Obi et al., 2016; Ochieng et al., 2013). Reduced fuel consumption increases thermal efficiency (Obi et al., 2016), and thus, evaluating thermal performance is essential in this study. From the findings, the traditional cooking practice, three-stone open fire, consumed almost 80% more fuelwood in average which led to much lower thermal efficiency than improved cooking practice using TLUD gasifier. In average, the thermal efficiency of cooking with three-stone open fire investigated in Waa County was found to be 8%, almost within the range of thermal efficiency of the same cooking method previously studied, 10-15% (Adria et al., 2013). The very low thermal efficiency of three-stone open fire investigated in this study shows that the decision of introducing energy-efficient cookstoves such as Gastov TLUD gasifier which had 17.67% of thermal efficiency, could bring multiple benefits to the people of Waa Ward, as well as other rural areas in Kenya.

Moreover, other fuels available in the farm, including crop residues, are abundant on farms, although require technological enhancement to be working as cooking fuel. Pyrolysis cookstove is capable to utilise these additional resources for cooking energy. For smallholder farmers like in Waa Ward, Kwale, biomass is not limitedly used as cooking fuel but also provides other services in the household farms, including construction material and animal fodder, although these services were excluded in this study based on the observation on the field. The Gastov (TLUD gasifier) a type of improved cookstove, provided as part of The Biochar Project to the households in the studied area has been continuously used for cooking as it has caused positive impacts to the cook of the house. From the informal interview with the cooks during Kitchen Performance Test (KPT), the cooks, mostly women, experience direct impacts and positive changes after using the Gastov. One of the direct positive impact is less smoke in the kitchen and the other impact is much lesser fuel used for cooking using the Gastov (Gitau et al., in press).

Similar to the traditional cooking method, neem and casuarina trees were majorly used as fuelwood when cooking with improved cookstove in Waa Ward, Kwale. The total energy from all sources of woody biomass was 63.70 MJ per household per day which can supply all the energy needs to fulfil household cooking when using improved cookstove, TLUD gasifier (see Chapter 4.1.1). The total energy was estimated from average data from all twelve household participants in this study. Therefore, the current production of biomass energy in the studied household farms is capable of satisfying and sustaining current cooking energy needs if using TLUD gasifier.

As discussed, lesser fuel need means higher thermal efficiency of the stoves (Obi et al., 2016). The average thermal efficiency of TLUD gasifier determined from observing 12 households in Waa Ward was found to be 18%, which was lower than previously studied. In the previous studies, thermal efficiencies achieved by gasifier cookstoves were within 25-50% (Bhattacharya et al., 2005; Mukunda et al., 2010). Based on the tests by KIRDI, the developer of TLUD gasifier cookstove used in Waa County, the gasifier attained 30% of thermal efficiency (Gituku et al., 2011). The method used for determining cookstove performance by KIRDI was water boiling test under laboratory conditions, which means there are several variables affecting the performance that were not considered in the lab test.

In the study of TLUD gasifier cookstove by Obi et al. (2016), the highest thermal efficiency achieved when using wood chips as fuel was 15.17%. In this study, the highest thermal efficiency was found, 42%, at Household 11. During the KPT at this household, it was discovered that the cook has been using TLUD gasifier daily and has developed the most efficient way for cooking for their household. The other cooks mostly started cutting the ingredient for cooking once the they started cooking, the cook in this household usually prepared and cut all the ingredients before started to fire up the cookstove. By doing this, a lot of time could be saved and therefore increased the thermal efficiency. This aligned with findings in a study by Berrueta et al. (2008), that differences in household cooking behaviour and cooking conditions might contribute to large variability in energy consumption that leads to variability in thermal efficiency. Another factor that cause poor performance of TLUD gasifier cookstove could be attributed to the inadequate concentration of the flame directly under the cooking pot, which could be caused by high inflow air to the combustion chamber through air inlet located at the bottom of the stove resulting in fast combustion of the fuel.

The other essential factor of using improved cookstove is the selection of feedstock. A lower consumption of fuelwood is desirable from environmental and health perspectives. Reduced wood consumption can reduce unsustainable extraction of fuelwood and less time for sourcing the fuelwood for cooking. In the studied area, the household participants majorly sourced their cooking fuel from their own farm by pruning method, which also means reducing the environmental burden by preventing the unsustainable extraction. Sourcing wood from out of their farm, also called off-farm, would likely causing unsustainable extraction if live trees are cut down. As has been discussed, out of ten different species of trees available in Waa Ward, the most preferred fuelwood for cooking by the cooks were neem and casuarina trees. Although the average thermal efficiency was slightly lower in cooking with neem woods, however, the calorific value of casuarina was higher than neem. These findings agree with the fact that casuarina tree has been recognised as the best firewood with calorific value of 5000 kcal/kg while neem tree has been long used as firewood (Orwa et al., 2009a; Orwa et al., 2009b).

Since the field observation was done during the planting season, therefore using crop residues as cooking fuel could not be assessed. There are upsides and downsides of not using crop residues. Returning biochar, a char product when cooking with pyrolysis stove, to the soil is important for soil conservation (Scholz et al., 2014). The addition of biochar to soil may prevent decrease of soil fertility by providing a source of organic matter which is recalcitrant (Zimmerman et al., 2011) and able to improve soil fertility (Kimetu et al., 2008). Without applying biochar to soil, the use of crop residues for bioenergy will possibly lead to a decline in soil organic matter and soil fertility (Lehmann and Joseph, 2015). The selection of feedstock in this study is, therefore, aligns with the objective of reducing deforestation rate and other environmental burdens, including reducing emissions.

5.1.3. Future significances on energy consumption patterns with the use of an improved cookstove

The fieldwork shows the capability of household farms in Waa Ward, Kwale, to sustain their current cooking energy needs. In addition to the energy availability assessment, the cooking performance was also analysed in order to obtain the cooking energy in different household. The introduction of an improved cookstove, TLUD gasifier, in the area, has demonstrated multiple benefits including biomass management and farm management. Increased farm performance can be attributed to the addition of biochar produced by TLUD gasifier to farm soil. The effect of addition of biochar to soil and the decrease in crop residues return has not been studied particularly in this study or largely under the Biochar Project.

In this study, households using a traditional three-stone open fire consume wood energy of 5.78 MJ per capita per meal or approximately 17.3 MJ per capita per day by assuming that cooking each of the three meals in a day consume the same amount of energy. The introduction of improved cookstove, TLUD gasifier cookstove, reduced energy consumption by 28.2 % or 4.15 MJ per capita per meal. A traditional three-stone open fire studied by Torres-Rojas et al. (2011) in Western Kenya consumed 19.5 MJ per capita per day, with a 27% of overall wood energy reduction for pyrolysis cookstove with 18.4 MJ per capita per day. In addition, a study carried out in a laboratory and controlled condition by MacCarty et al. (2008), achieved overall wood energy reductions of 47% with improved cookstoves built on the principle of gasification. Findings in this study found that the wood energy reductions similar with the study by Torres-Rojas et al. (2011), despite the contrast in the test and assessment methods carried out in this study. The introduction of TLUD gasifier to some household farms in Waa Ward, Kwale, have led to increases in energy efficiency, bearing in mind that the opportunity of improvements in TLUD gasifier cookstove design is always open. Lastly, the improved cookstove should be financially accessible to the end user, in this case, smallholder farmers. The high adoption rate of improved cookstove can be accomplished due to rapid return on investment. The socio-economic assessment should be done to assess the financial related issue. This largely happens in the area where the cost of fuel is already high and source of firewood is limited (Jeuland and Pattanayak, 2012).

Besides increased energy efficiency, the improved cookstove used in this study, TLUD gasifier also produces biochar. The average biochar that can be produced in a household is 0.21 kg per meal. From last year's crop trial data obtained from the same household participants showed the average biochar application rate of 0.31 kg/m^2 that led to average 285% and 512% maize crop yield increased with and without fertilisation, respectively. Similar to the uncontrolled condition under KPT, the biochar trials done in 2017 was also uncontrolled, which means that the farms had the full responsibility of deciding the biochar and fertiliser application rate. The amount of biochar rate applied was lesser by half of the amount of biochar applied in the study by Kimetu et al. (2008) of 0.6 kg/m^2 that caused 26% and 155% crop yield increased with and without nitrogen fertilisation, respectively. The study of biochar in Waa Ward, Kwale, has demonstrated a substantial increase of crop yield. It may be possible that the type of feedstock used to produce biochar, type of soil, and the age conversion of the land affected the crop yield (Torres, 2011).

5.1.4. Uncertainties and limitations of biomass measurement

The highest uncertainty from the field findings remains in the methodology of estimating the availability of woody biomass on the farms. In this study, the estimation was performed by manually counting the total trees grown on the farm and finally weighing the wet biomass after pruning. The area of the farm was obtained through the respective farmer's own estimation and the age of trees was also determined according to the farmer's memory, hence, large uncertainties because of these factors alone could be caused. Given enough resources, the method used in this study was the most appropriate since there was no existing knowledge about biomass availability given in the studied area and more precise measures of biomass availability were required. Although the similar method has been used before by Bilandzija (2012), more accurate measures can be obtained with other methods such as using allometric relationship and destructive sampling.

Destructive sampling is not the most ideal method for estimating total aboveground biomass for agricultural lands (Torres-Rojas et al., 2011). Although the destructive sampling in the study by Torres-Rojas et al. (2011) was performed on the harvested biomass and followed farmer's activities which eventually not wasted as the biomass used as firewood. Applying allometric relationship to estimate aboveground woody biomass availability has been used in several studies (Torres-Rojas et al., 2011; Chave et al., 2014; Henry et al., 2009). The results from this study demonstrated reasonably accurate results in estimating carbon stock and available woody aboveground biomass. Allometric relationship is also a not labour intensive method, and thus, the allometric relationship can be the most desired method for estimating available biomass.

5.2. Climate Change Impacts

This section discusses the findings from assessing climate change impacts of biochar system in Waa Ward, Kwale, using Life Cycle Assessment (LCA). As discussed in the previous study of climate change impact assessment by Sieber (2016), the results of a partial LCA as this one should be carefully interpreted as well as thoroughly incorporating factors that are not reflected in GWC as a single metric. Implications of the climate change impact of biochar systems in Kwale for stakeholders are presented thereafter.

5.2.1. Parameters and assumptions

Available biomass and feedstock consumed

The type and mass of available feedstocks in the farms vary greatly as previously discussed. The model of previous climate impact assessment under The Biochar Project by Sieber (2016) modelled all available on-farm biomass as feedstock. Due to limited local data from The Biochar Project, Sieber et al. (2016) assumed that all feedstocks and farm characteristics were the same and the generic values were employed for the model farm. The same assumptions were also modelled by Scholz et al. (2014) to assess the biochar system in Kenya in general. Nevertheless, the different approaches and assumptions were different in this study. The values of feedstock consumed by traditional and improved cooking methods were based on the fieldwork. Site-dependent data like in this case can reduce uncertainty compared to using generic defaults (Finnveden et al., 2009). Since

Fraction of non-renewable biomass

Fraction of non-renewable biomass (fNRB) has been discussed as one of the critical factor in assessing bioenergy system, in particular with projects where biomass fuel is decreased through e.g. improved cookstoves, just like in this study (Whitman et al., 2010). fNRB values for the assessment was obtained through biomass measurement, where it was investigated that two participant households do not plan to regrow the feedstocks used during observation. Renewability decides whether biogenic carbon emitted during combustion process or sequestered in biochar is considered to be equally absorbed as carbon dioxide during plant regrowth. In this study, however, this issue was not addressed due to different modelling (i.e. dynamic modelling) approach which lies beyond the aim of this study.

Cooking performance and emission factors

Similar to the input value of feedstock consumed to the model, the value of cooking performance inputted to the model was also based on the field observation. The main parameter of cooking performance is thermal efficiency, as previously shown in other studies that thermal efficiency is directly affecting the level of damaging emissions, namely particulate matters (PM) and carbon monoxide (CO). While thermal efficiency was estimated from the data during KPT, the emissions data used for the model had to be generalised for all calculated thermal efficiencies due to lack of direct measurement results. Although the direct emission measurement was also taken during the KPT, the results from the measurement was still not ready to be used in this study due to time constraint. Therefore, using generalised emission factors adopted from several studies with different methods might have caused large uncertainties on the results.

Net carbon sequestration and permanence

Biochar produced from unsustainably harvested stocks generates a net carbon flow to the atmosphere, due to the losses during conversion and the labile carbon fraction. In the other words, biochar does not sequester more carbon than bound in the feedstock before harvesting (Whitman et al., 2010). Climate mitigation of biochar system can only be obtained if the biomass used for producing biochar is renewable and regrown, and thus, absorbing additional carbon dioxide from the atmosphere. Stable carbon in biochar directly sequesters the carbon dioxide resulting in GHG offsets, as seen in the results. The stability of biochar relies on the carbonisation process as well as on climate and soil conditions (Scholz et al., 2014; Lehmann and Joseph, 2015). Biochar has a typical stable carbon content of 45% - 92% (Singh et al., 2012). In this study, 80% recalcitrant fraction and 500 years of mean residence time (MRT) was used as these assumptions were well-established in the literature (Scholz et al., 2014; Whitman et al., 2010).

5.2.2. Comparative: reference versus improved system

The comparative LCA was performed in attempt compare the climate change impacts of the reference system and the improved system. Based on the feedstock consumption, the consumption of fuel the improved cookstove generally met with sustainable on-farm supplies. The assessment found that with using an extended pollutant set, Set 2, and a time frame of 20-years, GWP_{20}, the improved system reduced an average of 89% of climate change impacts caused by the reference system. This result is almost similar with findings in Sieber (2016), 86% of saving by biochar system. Using only Kyoto gasses, Set 1, and time frame of 100-years, GWP_{100}, the improved system reduced the climate change impacts by 274% in average. These results suggest that the improved system does not only fully offset GHG emissions caused by traditional cooking method but also generates a net carbon credit.

5.2.3. Stand-alone: hotspots in improved system

While comparative assessment showed that improved system can bring more climate advantages to smallholder farms in the studied area, the stand-alone assessment was performed to compare all the 12 households participating in this study using the improved cookstove. Stand-alone assessment also contribute to locate the hotspot of the improved system. The main differences of the reference system and the improved system are located on the cooking process and the application of the by-product. In particular, the product of reference system was assumed to be eliminated from the system boundary as ash was not normally used at the studied area. While, the product of improved system, biochar, was used as a soil amendment.

The results from assessing twelve participant households under the improved system, has proven that CO_2 and carbon sequestration in biochar plays an important factor of the improved system that leads to climate mitigation. Although the cooking emissions caused by TLUD gasifier cookstove are relatively much lower than traditional three-stone open fire - determined with Kyoto gasses and GWP_{100} – the assessment demonstrated that the ‘hotspot’ of the improved system was recognised from the cooking process.

Finally, the improved system was significantly affected when feedstocks were 100% non-renewable (fNRB = 100%). This scenario was likely to happen at household 6 and household 10, since both households were planning not to regrow the feedstocks used for cooking at the time when fieldwork was conducted. Totally non-renewable biomass was included in sensitivity analysis in the study by Sieber (2016). The effects of 100% non-renewable feedstocks used are: 1) losses of credit for emissions from renewable biomass; 2) biochar produced from non-renewable biomass does not allocate net carbon sequestration, while releasing its fraction of labile carbon to the atmosphere; 3) and applying biochar to soil will most likely increase the system's GWC. Therefore, the most ideal scenarios under the improved system are applying biochar produced by renewable biomass to soil as soil amendment.

5.2.4. Biochar as a soil amendment

The assessment of biochar application to soil was intended to determine the climate change impacts when biochar is applied to soil and to compare when biochar is not applied to soil under the reference system. Crop response after biochar applied was included in the model to demonstrate that applying biochar to soil not only stores its recalcitrant carbon, it has also been proven to enhance soil properties as well as reduce GHG emissions. Biochar effect on crop response, growth and yield, depends on soil condition, biochar and crop type, as well as the application rate (Sohi et al., 2010). Sparrevik et al. (2013) discussed the importance to study the effect of biochar application to sandy and/or weathered soil. Due to geographical location, the studied area, Waa Ward, Kwale has sandy type of soil, and thus, the agronomic effect was assessed in this study. The data of crop response used in this study was obtained from 2017 crop trials under The Biochar Project in Waa Ward, Kwale. The assumptions of agronomic effect of applying biochar was expressed in kg/m^2 in order to simplify the quantification of biochar produced per capita.

The participant households have 1 – 4 hectares of land, with an average of 2.3 hectares, which was not entirely used to grow trees or other type of biomass. The plot trial was performed with using maize crops on 4 by 5 square metres. Conservatively, the whole farming area was assumed to be used for growing crops and treated with biochar. Based on the results from 2015, it was discovered that the most effective application rate on the fertilised samples had to be under 1 -10 ton/ha, otherwise further plant productivity would not be reached. The application rate of biochar was not controlled during the 2017 crop trials and the highest application rate was up to 5.5 ton/ha of biochar. Long term effect of biochar in soil as it remains stable over decades also cause positive impact on agronomical activities (Whitman et al., 2010), at least for several growing seasons. The second trial was being executed as this study was presented in the area to see whether the effect of biochar continues after a year. Nonetheless, the lack of long-term studies at The Biochar Project itself or at the other project could fail to validate this assumption.

Blackwell et al. (2009) describes the direct and indirect impacts of biochar application to the GHG balance, such as reduced non-CO_2 emission, increased plant productivity, reduced land conversion, and improved water-holding capacity are amongst many impacts. These factors were not considered in this study due to low contribution to the total GHG balance was estimated between 0 – 5% (Scholz et al., 2014).

5.2.5. Quantification of sensitivity

Sensitivity analysis was conducted in order to evaluate the variability in the results of LCA as a function of varying key input parameters. Both tested parameters, fraction of stable carbon in biochar and fraction of non-renewable biomass was shown to be major drivers in biochar system in Waa Ward, Kwale. GWC is expected to be insensitive when the variability is less than around 10% (Scholz et al., 2014, p. 95). The fraction of the stable carbon in the biochar within the realistic range of 50%-90%, influenced the GWC of improved system by -44% and 15%, respectively, and thus, contributed to relatively big influence on the results. Furthermore, GWC was investigated to be more sensitive to the fraction of non-renewable biomass, where the results showed that if all the biomass was non-renewable, more than 500% increased of GWC is seen in the improved system.

Findings from sensitivity analysis are aligned with study by Whitman et al. (2010), that the fraction of non-renewable biomass is critical especially at the area where biomass is non-renewable. Although almost all households regrow their fuel biomass, but there might be a potential change in the future if factors, e.g. economy, do not support the re-growing biomass, then biochar system would be impractical. Because if the biomass is regrown and harvested sustainably, then any carbon produced in biochar is considered as sequestered CO_2. If the biomass is not regrown, carbon in biochar counts as a net GHG emissions.

If the biomass is harvested from renewable biomass, then any carbon in produced biochar counts as sequestered CO_2. In contrast, carbon in biochar is not considered to be a change from the reference system if it is produced from non-renewable biomass. This approach is used because, even though biochar would be more stable than fresh biomass in the long term, promoting non-renewable biomass to produce biochar would be problematic because there are numerous critical non-carbon benefits of sustaining living biomass stocks. By introducing a biochar system to a region where fuel biomass is non-renewable would cause higher climate change impact and, therefore, the estimation of fNRB for the baseline scenario is critical.

5.2.6. Remaining uncertainties and improvements suggestion

The biggest uncertainty of LCA is discovered at emission factors, especially when the aim of this study was to assess climate change impact as real as possible. To identify the connection between thermal efficiency, energy delivered to the pot, and pollutant ratios in the studied area require more time and broader scope. The other uncertainty is the type and amount of feedstock as the calculations made in this study was based on one-time observation. Different species of fuelwood used for cooking different meal of the day, i.e. breakfast and lunch, might lead to different results. This study also did not consider whether the ‘actual’ type of fuelwood normally used for cooking every day would or would not meet the needs due to complicated quantifications.

In the literature review, studies of agricultural impact of biochar application were mainly done in other regions, different soil type as well as different climate, making data from these literatures invalid for this study. Therefore, in the case of estimating agricultural emissions, Cool Farm Tool was utilised to avoid further bias. Some missing data from Plot Trials under The Biochar Project in Waa Ward, e.g. type of fertiliser, was taken from literatures.

The last uncertainty of this study lies on the tool utilised to model the LCIA. Using Pivot has upsides and downsides in this study. The advantage is that it saves time when testing several assumptions and scenarios simultaneously. The remarkable feature of Pivot is that it allows testing different combinations, including different pollutants and GWP at the same time, as GWP largely effects the results in absolute terms. However, testing more than one model farm was complicated as each model has to be evaluated individually.

By combining the results of LCA and fieldwork, some measures that can be suggested to be implemented by stakeholders in Waa Ward, Kwale County, are listed in Table 5.1.

Table 5. 1. *Suggestions for improvement based on the life cycle assessment*

Module	**Measures**	**Stakeholder**
Feedstock	Practice regrowing trees used for fuelwood	Farmers
	Develop usage of crop residues as fuel, even during non-harvesting seasons, to reduce consumption of woody biomass	Farmers
	Increase the frequency of using TLUD gasifier in a day, from once to twice daily at least	Farmers
Cookstove and cooking	Implement improved cookstove in rural areas to reduce fuel consumption, especially in the area where fuel is scarce	Government
	Improve the design of TLUD cookstove to reduce time to light up for cooking	Manufacturer
	Use locally manufactured materials to build TLUD gasifier in order to reduce transportation emissions	Manufacturer
	Prepare the fuel in advance to increase combustion efficiency	Farmers
	Prepare ingredients for cooking in advance to shorten cooking time that leads to reduced fuel consumption and increased thermal efficiency	Farmers
	Cover the cooking vessel during cooking to reduce heat losses	Farmers
	Increase kitchen's ventilation to reduce indoor air pollution	Farmers
	Harvest biochar once it fully carbonised during cooking process to maximise the potential of biochar	Farmers
Biochar application	Store biochar in a dry place	Farmers
	Produce and apply biochar only from renewable biomass	Farmers

Chapter 6: Conclusions and Future Work

6.1. Conclusions

In this study, climate change impact of a biochar system in Kwale, Kenya was assessed and compared to the traditional system. Climate change impact was assessed with LCA. The aim of this study was to compare the reference system and the improved system. The main differences of the two systems were the type of cooking techniques used and the application of the byproducts. Under the reference system, traditional three-stone open fire was used for cooking and the by-product, ash, were omitted from the assessment. The improved system used a cookstove, TLUD gasifier type, for cooking and applied the by-product, biochar, to soil as soil amendment. The improved system has the potential to mitigate climate change through GHG emissions reductions and carbon sequestration.

During field observation in Kwale, Kenya, in April 2018 – May 2018, biomass availability and cooking performance in different households were investigated. A great variability in biomass availability discovered in different households could be caused by different factors, from land conversion age to financial. Cooking with Gastov, the TLUD gasifier cookstove used in the Biochar Project, was found to lead an overall better performance than cooking with traditional three-stone open fire. The only disadvantage of cooking with Gastov investigated during KPT would be the time to start the fire was significantly longer than lighting up fire with three-stone open fire. Lastly, it was found that all the participant households have been using the TLUD gasifier cookstove at least once a day in average, an improvement from the previous study where only 35% of the households used the gasifier on daily basis.

The comparative LCA demonstrates that even under the worst scenario, cooking with TLUD gasifier shows benefits over the traditional cooking practice with three-stone open fire. The synergistic advantages of improved system (biochar system) in Kwale may include decreased indoor air pollution through avoided inefficient combustion, decreased fuelwood consumption and thereby reduced deforestation pressures, offset the relatively small climate impact caused by gasifier cookstoves through carbon sequestration, and improved long-term soil fertility through application of biochar.

The contribution analysis performed under stand-alone LCA revealed that the net GHG balance is widely caused by the renewability of the feedstock. If the feedstock for cooking is not regrown, the emissions during cooking are subsequently not offset by the biomass regrowth. Further, stable carbon was the largest GHG reductions in all participant households, except for two households with non-renewable biomass used for feedstocks. All the emissions from cooking, transportation and agriculture activities, in most cases, would be cancelled out by the amount of stable of carbon in the biochar if biomass was produced sustainably.

The sensitivity analysis demonstrates that GWC is sensitive to the fraction of non-renewable biomass and the fraction of stable carbon in biochar. The improved system is most sensitive to the fraction of non-renewable biomass confirming that applying biochar produced from non-renewable and unsustainably harvested biomass would lead to unsuccessful results of biochar application in respect to climate change mitigation.

6.2. Future work

Many assumptions had to be made in this study due to lack of time, in particular with the emissions factor. Future work concerns deeper assessment of ‘real time’ scenario using the emissions data obtained during field observation. It is important to establish the emission factors for the TLUD gasifier as there is no current literature data available to actually characterise the char-producing improved cookstove.

The two other uncertainties mentioned in this study was the method of biomass measurement and estimation method of agricultural emissions. The biomass availability measurement should be an independent research study as the nature of its large scope of study. There are some biomass measurement methods that could be tried including using the allometric relationship. The last uncertainty is the agricultural emissions estimation. Although The Biochar Project focuses more on the bioenergy and biochar application aspects, however, further studies of the effects of biochar application to soil has not been included in the LCA. It has been demonstrated in this study and several other studies that the application of biochar has a bigger contribution to climate change mitigation which needs to be further studied. Therefore, biochar effects to soil regarding GHG emissions would be interesting to analyse further.

Finally, a dynamic modelling approach would be more appealing as it can model the plant productivity and available feedstocks. As the net climate impact of biochar varies over with time, a dynamic model representing carbon stocks and flows modelled dynamically over time, would show a more accurate impact.

Bibliography

Adkins, E., Tyler, E., Wang, J., Siriri, D. & Modi, V., 2010. Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. *Energy for sustainable development,* 14(3)**,** pp. 172-185.

Adria, O., Bethge, J., WI, S. T., WI, A. D., WI, C. B., Volkmer, H. & Salow, S., 2013. What users can save with energy-efficient cooking stoves and ovens. *Wuppertal Institute for Climate, Environment and Energy*.

Akagi, S., Yokelson, R. J., Wiedinmyer, C., Alvarado, M., Reid, J., Karl, T., Crounse, J. & Wennberg, P., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmospheric Chemistry and Physics,* 11(9)**,** pp. 4039-4072.

Ali, A. & Erenstein, O., 2017. Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management,* 16(183-194.

Amonette, J. E. & Joseph, S., 2009. Characteristics of biochar: microchemical properties. *Biochar for environmental management: Science and technology,* 33(

Andae, G. 2014. Revealed: The best and worst counties for maize. *Daily Nation*, 21 February 2014.

Anon., 1999. Best available practice regarding impact categories and category indicators in life cycle impact assessment. *The International Journal of Life Cycle Assessment,* 4(3)**,** pp. 167.

Antal, M. J. & Grønli, M., 2003. The art, science, and technology of charcoal production. *Industrial & Engineering Chemistry Research,* 42(8)**,** pp. 1619-1640.

Awuor, C. B., Orindi, V. A. & Ochieng Adwera, A., 2008. Climate change and coastal cities: the case of Mombasa, Kenya. *Environment and Urbanization,* 20(1)**,** pp. 231-242.

Azapagic, A., 1999. Life cycle assessment and its application to process selection, design and optimisation. *Chemical engineering journal,* 73(1)**,** pp. 1-21.

Bai, Z., Dent, D., Olsson, L. & Schaepman, M. 2008. Global assessment of land degradation and improvement: 1. identification by remote sensing,

Bailis, R., Ezzati, M. & Kammen, D. M. 2003. Greenhouse gas implications of household energy technology in Kenya. ACS Publications.

Balamohan, T. N., Mekala, P., Rajadurai, S., Priyadharshini, G., Prakash, K., Soorianathasundaram, K. & Kumar, N. 2014. Canopy Management in Mango. *Value Chain Management in Mango.* India: Department of Fruit Crops Horticultural College and Research Institute, Tamil Nadu Agricultural University.

Basu, P. 2013. *Biomass gasification, pyrolysis and torrefaction: practical design and theory*: Academic press.

Baumann, H. 1998. *Life cycle assessment and decision making: theories and practices*: Chalmers University of Technology.

Berrueta, V. M., Edwards, R. D. & Masera, O. R., 2008. Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renewable Energy,* 33(5)**,** pp. 859-870.

Bhattacharya, S., Hla, S., Leon, M. & Weeratunga, K., 2005. An improved gasifier stove for institutional cooking. *Asian Institute of Technology, Thailand*.

Bilandzija, N., 2012. Energy potential of fruit tree pruned biomass in Croatia. *Spanish Journal of Agricultural Research,* 2)**,** pp. 292-298.

Blackwell, P., Riethmuller, G. & Collins, M., 2009. Biochar application to soil. *Biochar for environmental management: science and technology,* 1(207-226.

Bond, T., Venkataraman, C. & Masera, O., 2004a. Global atmospheric impacts of residential fuels. *Energy for Sustainable Development,* 8(3)**,** pp. 20-32.

Bond, T. C., Doherty, S. J., Fahey, D., Forster, P., Berntsen, T., DeAngelo, B., Flanner, M., Ghan, S., Kärcher, B. & Koch, D., 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres,* 118(11)**,** pp. 5380-5552.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J. H. & Klimont, Z., 2004b. A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres,* 109(D14)**,** pp.

Boulkaid, Y. 2015. Quantifying the Potential Impact of Improved Stoves in Nyeri County, Kenya.

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S. & Herrero, M., 2013. Adapting agriculture to climate change in Kenya: Household strategies and determinants. *Journal of environmental management,* 114(26-35.

Bunchan, S., Poowadin, T. & Trairatanasirichai, K., 2017. A Study of Throat Size Effect on Downdraft Biomass Gasifier Efficiency. *Energy Procedia,* 138(745-750.

Carter, S. & Shackley, S., 2011. Biochar Stoves: an innovation studies perspective. *UK Biochar Research Centre, University of Edinburgh*.

Cefic-ECTA, 2011. Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations. *Cefic Report,* 1(1-18.

Chan, K. Y. & Xu, Z., 2009. Biochar: nutrient properties and their enhancement. *Biochar for environmental management: science and technology,* 1(67-84.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., Duque, A., Eid, T., Fearnside, P. M. & Goodman, R. C., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology,* 20(10)**,** pp. 3177-3190.

Climate Watch. 2018. *Climate Watch: Kenya* [Online]. Available: https://www.climatewatchdata.org/countries/KEN [Accessed 20 May 2018].

Coffey, E. R., Muvandimwe, D., Hagar, Y., Wiedinmyer, C., Kanyomse, E., Piedrahita, R., Dickinson, K. L., Oduro, A. & Hannigan, M. P., 2017. New Emission Factors and Efficiencies from in-Field Measurements of Traditional and Improved Cookstoves and Their Potential Implications. *Environmental Science & Technology,* 51(21)**,** pp. 12508-12517.

Couto, H., Duarte, F. & Bastos-Netto, D. Biomass combustion chamber for cashew nut industry. Proceedings of the Seventh Asia-Pacific International Symposium on Combustion and Energy Utilization, 2004.

Curran, M. A., Mann, M. & Norris, G., 2005. The international workshop on electricity data for life cycle inventories. *Journal of Cleaner Production,* 13(8)**,** pp. 853-862.

De Bruijn, H., van Duin, R. & Huijbregts, M. A. 2004. Handbook on life cycle assessment. Springer.

Engineering ToolBox. 2003. *Specific Heat of Food and Foodstuff* [Online]. Available: https://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html [Accessed 01 June 2018 2018].

Erakhrumen, A., Ogunsanwo, O. & Ajewole, O., 2010. Assessment of some other traditional uses of accepted agroforestry fuelwood species in akinyele and ido local government areas, Oyo State, Nigeria. *International Journal of Social Forestry,* 3(1)**,** pp. 47-65.

Ezzati, M. & Kammen, D. M., 2001. Indoor air pollution from biomass combustion and acute respiratory infections in Kenya: an exposure-response study. *The Lancet,* 358(9282)**,** pp. 619-624.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S., 2009. Recent developments in life cycle assessment. *Journal of environmental management,* 91(1)**,** pp. 1-21.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. & Dorland, R. V. 2007. Changes in atmospheric constituents and in radiative forcing, (New York, NY).

Frolkis, V. A., Karol, I. L. & Kiselev, A. A., 2002. Global warming potential, global warming commitment and other indexes as characteristics of the effects of greenhouse gases on Earth's climate. *Ecological Indicators,* 2(1-2)**,** pp. 109-121.

Garrett, S., Hopke, P. & Behn, W. A Research Road Map: Improved Cook Stove Development and Deployment for Climate Change Mitigation and Women's and Children's Needs. Report to the US State Department from the ASEAN-US, Next-Generation Cook Stove Workshop, 2010.

Gaunt, J. & Cowie, A., 2009. Biochar, greenhouse gas accounting and emissions trading. *Biochar for environmental management: Science and technology,* 317-340.

Giller, K. E., Tittonell, P., Rufino, M. C., Van Wijk, M. T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R. & Corbeels, M., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural systems,* 104(2)**,** pp. 191-203.

Gitau, J. K., Mutune, J., Sundberg, C., Mendum, R. & Njenga, M. In press. Factors influencing the uptake of microgasification cooking system among rural farmers. Nairobi, Kenya.

Githiomi, J. & Oduor, N., 2012. Strategies for sustainable wood fuel production in Kenya.

Gituku, B., Mwitari, P., Kamau, E. J. & Makayoto, M. 2011. Development and commercialization of gasifier stoves at KIRDI. 7 June 2011 ed. Kenya.

Government of Kenya. 2010. Agricultural Sector Development Strategy 2010-2020, Government of Kenya (Kenya).

Government of Kenya. 2013. National Climate Change Action Plan: 2013 - 2017. 31 March 2013 ed. Kenya: Government of Kenya, National Cimate Change Action Plan.

Government of Kenya. 2016. Kenya National Adaptation Plan 2015-2030: Enhanced climate resilience towards the attainment of Vision 2030 and beyond. March 2016 ed. Kenya: Government of Kenya.

Grieshop, A. P., Marshall, J. D. & Kandlikar, M., 2011. Health and climate benefits of cookstove replacement options. *Energy Policy,* 39(12)**,** pp. 7530-7542.

Guibal, D., Cerre, J.-C., Gérard, J. & Paradis, S. 2017. *Tropical Timber Atlas: Technological characteristics and uses*: Quae.

Guinée, J., 2001. Handbook on life cycle assessment—operational guide to the ISO standards. *The international journal of life cycle assessment,* 6(5)**,** pp. 255-255.

Gwenzi, W., Chaukura, N., Mukome, F. N., Machado, S. & Nyamasoka, B., 2015. Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. *Journal of environmental management,* 150(250-261.

Hauschild, M. Z. & Huijbregts, M. A. J. 2015. *Life Cycle Impact Assesment*: Springer.

Haverkort, A. & Hillier, J., 2011. Cool farm tool–potato: model description and performance of four production systems. *Potato Research,* 54(4)**,** pp. 355-369.

Heijungs, R. & Suh, S. 2013. *The computational structure of life cycle assessment*: Springer Science & Business Media.

Henry, M., Tittonell, P., Manlay, R. J., Bernoux, M., Albrecht, A. & Vanlauwe, B., 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. *Agriculture, ecosystems & environment,* 129(1-3)**,** pp. 238-252.

Hillier, J., Walter, C., Malin, D., Garcia-Suarez, T., Mila-i-Canals, L. & Smith, P., 2011. A farm-focused calculator for emissions from crop and livestock production. *Environmental Modelling & Software,* 26(9)**,** pp. 1070-1078.

Iiyama, M., Neufeldt, H., Dobie, P., Njenga, M., Ndegwa, G. & Jamnadass, R., 2014. The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Current Opinion in Environmental Sustainability,* 6(138-147.

IPCC. 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.

Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C. U. (Cambridge, United Kingdom and New York, NY, USA).

IPCC. 2014b. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, (Cambridge, United Kingdom and New York, NY, USA).

Jackson, N., Wallace, J. & Ong, C., 2000. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *Forest Ecology and Management,* 126(2)**,** pp. 133-148.

Jackson, S. C., 2009. Parallel pursuit of near-term and long-term climate mitigation. *Science,* 326(5952)**,** pp. 526-527.

Jerrett, M., Burnett, R. T., Pope III, C. A., Ito, K., Thurston, G., Krewski, D., Shi, Y., Calle, E. & Thun, M., 2009. Long-term ozone exposure and mortality. *New England Journal of Medicine,* 360(11)**,** pp. 1085-1095.

Jeuland, M. A. & Pattanayak, S. K., 2012. Benefits and costs of improved cookstoves: assessing the implications of variability in health, forest and climate impacts. *PloS one,* 7(2)**,** pp. e30338.

Jørgensen, A., Le Bocq, A., Nazarkina, L. & Hauschild, M., 2008. Methodologies for social life cycle assessment. *The international journal of life cycle assessment,* 13(2)**,** pp. 96.

Kabubo-Mariara, J. & Karanja, F. K., 2007. The economic impact of climate change on Kenyan crop agriculture: A Ricardian approach. *Global and planetary change,* 57(3-4)**,** pp. 319-330.

Kaygusuz, K., 2011. Energy services and energy poverty for sustainable rural development. *Renewable and Sustainable Energy Reviews,* 15(2)**,** pp. 936-947.

Kenya Agricultural Research Institute. 2012. Policy Responses to Food Security in Kenya,

Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S., Verchot, L., Recha, J. W. & Pell, A. N., 2008. Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems,* 11(5)**,** pp. 726.

Kiplagat, J., Wang, R. & Li, T., 2011. Renewable energy in Kenya: Resource potential and status of exploitation. *Renewable and Sustainable Energy Reviews,* 15(6)**,** pp. 2960-2973.

KIRDI. 2016. GASTOV 206 & 212 OPERATION MANUAL. (Nairobi, Kenya).

Kituyi, E., Marufu, L., Huber, B., Wandiga, S. O., Jumba, I. O., Andreae, M. O. & Helas, G., 2001. Biofuel consumption rates and patterns in Kenya. *Biomass and Bioenergy,* 20(2)**,** pp. 83-99.

Klöpffer, W. & Grahl, B. 2014. *Life cycle assessment (LCA): a guide to best practice*: Wiley-VCH.

Lal, R. & Singh, B., 1998. Effects of soil degradation on crop productivity in East Africa. *Journal of Sustainable Agriculture,* 13(1)**,** pp. 15-36.

Lehmann, J., Czimczik, C., Laird, D. & Sohi, S., 2009. Stability of biochar in soil. *Biochar for environmental management: science and technology,* 183-206.

Lehmann, J., Gaunt, J. & Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems–a review. *Mitigation and adaptation strategies for global change,* 11(2)**,** pp. 395-419.

Lehmann, J. & Joseph, S. 2015. *Biochar for environmental management: science, technology and implementation*: Routledge.

Loo, J. D., Hyseni, L., Ouda, R., Koske, S., Nyagol, R., Sadumah, I., Bashin, M., Sage, M., Bruce, N. & Pilishvili, T., 2016. User perspectives of characteristics of improved cookstoves from a field evaluation in western Kenya. *International journal of environmental research and public health,* 13(2)**,** pp. 167.

MacCarty, N., Ogle, D., Still, D., Bond, T. & Roden, C., 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy for sustainable development,* 12(2)**,** pp. 56-65.

Major, J., Rondon, M., Molina, D., Riha, S. J. & Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and soil,* 333(1-2)**,** pp. 117-128.

McCarl, B. A., Peacocke, C., Chrisman, R., Kung, C.-C. & Sands, R. D., 2009. Economics of biochar production, utilization and greenhouse gas offsets. *Biochar for environmental management: Science and technology,* 341-358.

McKinnon, A. 2011. Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations.

Mensah, L. D., Buertey, K. L. & Kemausuor, F. 2017. Experimental Analysis of Three Common Tree Species in Ghana. *International Journal of Engineering Sciences & Research Technology.* Ghana: The Brew-Hammond Energy Center.

Midgley, S. J. & Sylvester, R. 2016. *Casuarina equisetifolia (PROSEA)* [Online]. Pl@ntUse. Available: https://uses.plantnet-project.org/en/Casuarina_equisetifolia_(PROSEA) [Accessed 05 June 2018].

Mukunda, H., Dasappa, S., Paul, P., Rajan, N., Yagnaraman, M., Kumar, D. R. & Deogaonkar, M., 2010. Gasifier stoves--science, technology and field outreach. *Current Science (00113891)*, 98(5)**,** pp.

Mutai, C. C., Ochola, S. O., Mukiira, H. K., Gachimbi, L. N., Otiono, M., King'uyu, S. M. & Marigi., S. N. 2011. State of the Environment – Chapter 3: Climate change and variability. 2011 ed. Kenya: National Environment Management Authority.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. 2013. Anthropogenic and Natural Radiative Forcing, Press, C. U. (Cambridge, United Kingdom and New York, NY, USA).

n.a. 2016. *How to grow cashew tree* [Online]. Available: http://balconygardenweb.com/how-to-grow-a-cashew-tree-growing-cashew-nuts/how-to-grow-cashew-tree/ [Accessed 01 June 2018].

Nabuurs, G., Garza-Caligaris, J., Kanninen, M., Karjalainen, T., Lapvetelainen, T., Liski, J., Masera, O., Mohren, G., Olgin, M. & Pussinen, A. 2002. CO2FIX V2. 0: manual of a modeling framework for quantifying carbon sequestration in forest ecosystems and wood products,

NEMA. 2009. National Environment Plan Framework 2009-2013. *In:* Authority, N. E. M. (ed.) March 2009 ed. Nairobi.

Njenga, M., Iiyama, M., Jamnadass, R., Helander, H., Larsson, L., de Leeuw, J., Neufeldt, H., Röing de Nowina, K. & Sundberg, C., 2016. Gasifier as a cleaner cooking system in rural Kenya. *Journal of Cleaner Production*, 121(208-217.

Obi, O. F., Ezeoha, S. L. & Okorie, I. C., 2016. Energetic performance of a top-lit updraft (TLUD) cookstove. *Renewable Energy*, 99(730-737.

Ochieng, C. A., Tonne, C. & Vardoulakis, S., 2013. A comparison of fuel use between a low cost, improved wood stove and traditional three-stone stove in rural Kenya. *biomass and bioenergy*, 58(258-266.

Ortiz-Gonzalo, D., Vaast, P., Oelofse, M., de Neergaard, A., Albrecht, A. & Rosenstock, T. S., 2017. Farm-scale greenhouse gas balances, hotspots and uncertainties in smallholder crop-livestock systems in Central Kenya. *Agriculture, Ecosystems & Environment*, 248(58-70.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R. & Anthony, S. 2009a. Azadirachta indica. Kenya: ICRAF World Agroforestry Centre.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R. & Anthony, S. 2009b. Casuarina equisetifolia. Kenya: ICRAF World Agroforestry Centre.

Otieno, H. O. & Awange, J. L. 2006. *Energy resources in East Africa: opportunities and challenges*: Springer Science & Business Media.

Pelletier, N., Ardente, F., Brandão, M., De Camillis, C. & Pennington, D., 2015. Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? *The International Journal of Life Cycle Assessment*, 20(1)**,** pp. 74-86.

Perez, S., Renedo, C., Ortiz, A., Manana, M., Silio, D. & Peredo, J. Comparison of energy potential of the Eucalyptus globulus and Eucalyptus nitens. International conference on renewable energy and power quality, 2006. 5-6.

Ramanathan, V. & Carmichael, G., 2008. Global and regional climate changes due to black carbon. *Nature geoscience,* 1(4)**,** pp. 221.

Rillig, M. C. & Thies, J. E. 2012. Characteristics of biochar: biological properties. *Biochar for environmental management.* Routledge.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R. & Lehmann, J., 2009. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental science & technology,* 44(2)**,** pp. 827-833.

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A., Temesgen, M., Mawenya, L., Barron, J., Mutua, J. & Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. *Soil and Tillage Research,* 103(1)**,** pp. 23-32.

Roden, C. A., Bond, T. C., Conway, S. & Pinel, A. B. O., 2006. Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. *Environmental science & technology,* 40(21)**,** pp. 6750-6757.

Ross, S. & Evans, D., 2002. Excluding site-specific data from the LCA inventory: how this affects life cycle impact assessment. *The International Journal of Life Cycle Assessment,* 7(3)**,** pp. 141-150.

Roth, C., Anderson, P., McLaughlin, H., Thomlinson, T. & Wilson, K. 2014. *Micro-gasification: cooking with gas from dry biomass*: GIZ.

Ruiz-Mercado, I., Masera, O., Zamora, H. & Smith, K. R., 2011. Adoption and sustained use of improved cookstoves. *Energy policy,* 39(12)**,** pp. 7557-7566.

Sanginga, N. & Woomer, P. L. 2009. *Integrated soil fertility management in Africa: principles, practices, and developmental process*: CIAT.

Scherr, S. J., 1995. Economic factors in farmer adoption of agroforestry: patterns observed in Western Kenya. *World development,* 23(5)**,** pp. 787-804.

Scholz, S. B., Sembres, T., Roberts, K., Whitman, T., Wilson, K. & Lehmann, J. 2014. *Biochar systems for smallholders in developing countries: leveraging current knowledge and exploring future potential for climate-smart agriculture*: World Bank Publications.

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M. & Reinhardt, J., 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change,* 17(6)**,** pp. 1585-1600.

Sieber, P. 2016. *Implication of improved biofuel management for climate change: An LCA-based evaluation of biochar and charcoal in Kenyan smallholder farming.* Master of Science Master's thesis, University of Natural Resources and Applied Life Sciences.

Singh, B. P., Cowie, A. L. & Smernik, R. J., 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental science & technology,* 46(21)**,** pp. 11770-11778.

Smale, M., Byerlee, D. & Jayne, T. 2013. Maize revolutions in sub-Saharan Africa. *an African green revolution.* Springer.

Smebye, A. B., Sparrevik, M., Schmidt, H. P. & Cornelissen, G., 2017. Life-cycle assessment of biochar production systems in tropical rural areas: Comparing flame curtain kilns to other production methods. *Biomass and Bioenergy,* 101(35-43.

Smith, K. R. & Haigler, E., 2008. Co-benefits of climate mitigation and health protection in energy systems: scoping methods. *Annu. Rev. Public Health,* 29(11-25.

Smith, K. R., Uma, R., Kishore, V., Zhang, J., Joshi, V. & Khalil, M., 2000. Greenhouse implications of household stoves: an analysis for India. *Annual Review of Energy and the Environment,* 25(1)**,** pp. 741-763.

Sohi, S., Krull, E., Lopez-Capel, E. & Bol, R., 2010. A review of biochar and its use and function in soil. *Advances in agronomy,* 105(47-82.

Sparrevik, M., Field, J. L., Martinsen, V., Breedveld, G. D. & Cornelissen, G., 2013. Life cycle assessment to evaluate the environmental impact of biochar implementation in conservation agriculture in Zambia. *Environmental science & technology,* 47(3)**,** pp. 1206-1215.

Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., Boateng, A. A., Lima, I. M., Lamb, M. C. & McAloon, A. J., 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *Journal of environmental quality,* 41(4)**,** pp. 973-989.

Stavi, I. & Lal, R., 2013. Agroforestry and biochar to offset climate change: a review. *Agronomy for Sustainable Development,* 33(1)**,** pp. 81-96.

Stocking, M. A., 2003. Tropical soils and food security: the next 50 years. *Science,* 302(5649)**,** pp. 1356-1359.

The Cool Farm Alliance. 2018. Cool Farm Tool 2.0. England.

Torres-Rojas, D., Lehmann, J., Hobbs, P., Joseph, S. & Neufeldt, H., 2011. Biomass availability, energy consumption and biochar production in rural households of Western Kenya. *biomass and bioenergy,* 35(8)**,** pp. 3537-3546.

Torres, D., 2011. Biochar production with cook stoves and use as a soil conditioner in Western Kenya.

UN General Assembly. 2013. United Nations Decade of Sustainable Energy for All 06 August 2013 ed.: United Nations.

UNEP, W., 2011. Integrated assessment of black carbon and tropospheric ozone: Summary for Decision Makers. *Nairobi: United Nations Environment Programme*.

Velázquez-Martí, B., López-Cortés, I., Salazar-Hernández, D. & Callejón-Ferre, Á. J. 2017. Modeling the Calorific Value of Biomass from Fruit Trees Using Elemental Analysis Data. *Biomass Volume Estimation and Valorization for Energy.* InTech.

Vitali, F., Parmigiani, S., Vaccari, M. & Collivignarelli, C., 2013. Agricultural waste as household fuel: Techno-economic assessment of a new rice-husk cookstove for developing countries. *Waste management,* 33(12)**,** pp. 2762-2770.

Wang, X., Zhou, W., Liang, G., Song, D. & Zhang, X., 2015. Characteristics of maize biochar with different pyrolysis temperatures and its effects on organic carbon, nitrogen and enzymatic activities after addition to fluvo-aquic soil. *Science of the Total Environment,* 538(137-144.

Wang, Z., Zheng, H., Luo, Y., Deng, X., Herbert, S. & Xing, B., 2013. Characterization and influence of biochars on nitrous oxide emission from agricultural soil. *Environmental pollution,* 174(289-296.

WBCSD CSI. 2014. *Lower and Higher Heating Values (LHV and HHV)* [Online]. Cement CO2 Protocol. Available: http://www.cement-co2-

protocol.org/en/Content/Internet_Manual/tasks/lower_and_higher_heating_values.htm [Accessed 01 June 2018].

Wheeler, T. & Von Braun, J., 2013. Climate change impacts on global food security. *Science,* 341(6145)**,** pp. 508-513.

Whitman, T. & Lehmann, J., 2009. Biochar—One way forward for soil carbon in offset mechanisms in Africa? *Environmental science & policy,* 12(7)**,** pp. 1024-1027.

Whitman, T., Nicholson, C. F., Torres, D. & Lehmann, J., 2011. Climate change impact of biochar cook stoves in Western Kenyan farm households: system dynamics model analysis. *Environmental science & technology,* 45(8)**,** pp. 3687-3694.

Whitman, T., Scholz, S. M. & Lehmann, J., 2010. Biochar projects for mitigating climate change: an investigation of critical methodology issues for carbon accounting. *Carbon Management,* 1(1)**,** pp. 89-107.

Wilkinson, P., Smith, K. R., Davies, M., Adair, H., Armstrong, B. G., Barrett, M., Bruce, N., Haines, A., Hamilton, I. & Oreszczyn, T., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet,* 374(9705)**,** pp. 1917-1929.

Wolf, M.-A., Chomkhamsri, K., Brandao, M., Pant, R., Ardente, F., Pennington, D. W., Manfredi, S., de Camillis, C. & Goralczyk, M., 2010. ILCD Handbook-General Guide for Life Cycle Assessment-Detailed Guidance.

Woomer, P. L., Bekunda, M. A., Karanja, N. K., Moorehouse, T. & Okaledo, J. R., 1998. Agricultural resource management by smallhold farmers in East Africa. *Nature and Resources,* 34(4)**,** pp. 22-33.

World Bank. 2017. World Development Indicators: Employment by sector. *In:* 2.3_Employment_by_sector (ed.). The World Bank Group.

Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L., Zheng, J. & Zhang, X., 2012. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. *Plant and soil,* 351(1-2)**,** pp. 263-275.

Zimmerman, A. R., Gao, B. & Ahn, M.-Y., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry,* 43(6)**,** pp. 1169-1179.

Zolho, A. H., 2008. MIOMBO COMMUNITY LAND USE & CARBON MANAGEMENT.

Appendices

Appendix A: Questionnaire Forms

Questionnaire Form

Date of the cooking test:

Ward:

Household name:

Family head:

Men: Women: Children (<15): Boys: Girls:

No. of cook stove: Type of cook stove:

No.	Observations	Findings
Fuels used during the test		
1	Fuel type used by the household for cooking	Firewood:
		Residue:
2	Source of fuel used	Firewood:
		Residue:
3	Place to keep the fuels	Firewood:
		Residue:
4	Duration of fuels stacked until filled again	Firewood:
		Residue:
5	Capacity of storage	Firewood:
		Residue:
6	Who prepares the fuel for cook	Sex:
		Transport:
7	When is the fuel prepared	a. At cooking time
		b. In advance within the same day
		c. In advance but on a different day
8	Process to prepare/process the fuel (process from biomass to fuel)	Firewood:
		Residue:
9	Which one is priority among the fuels	Firewood/Residue
	Reason	
10	Frequency of cook stoves in a day	3-stone:
		TLUD gasifier:
11	Reason of using cook stove more frequent	
12	By-product used	Ash:
		Biochar:
13	Other observations:	

Figure A. 1. *Questionnaire form template used during Kitchen Performance Test*

Template for fieldbased cooking test **Test number:**

Date: **Name of household:**

Name of fuel: **Type of stove:**

☐	GASTOV
☐	3-stone fire

Data of fieldbased performance test		
PARAMETERS	**Units**	**Test 1**
Weight of canister alone	g	
Weight of canister and fuel	g	
Start Weight of fuel (W1)	g	
Start time lighting (T1)	time	
Time when fuel catches fire (T2)	time	
Start time of cooking dish 1 (T3)	time	
Time when dish 1 ready (T4)	time	
Start time of cooking dish 2 (T5)	time	
Time when dish 2 ready (T6)	time	
Time fuel charred (T7)	time	
Time when char cools (T8)	time	
Weight of charcoal produced (C1)	g	
Weight of ash produced (S1)	g	
Gasifier round 1 calculations		
Time taken to light the stove (T2-T1)	time	
Time taken to char (T7-T2)	time	
Time taken for char to cool (T8-T7)	time	
Change Over 1		
Weight of canister and fuel 2	g	
Start weight of prepared fuel in change over 1 (W2)	g	
Start time to light the stove (T9)	time	
Time when fuel catches fire (T10)	time	
Start time to cook (T11)	time	
Finish time charring (T12)	time	
Time when char cools (T13)	time	
Weight of charcoal produced (C2)	g	
Weight of ash produced (S2)	g	
Gasifier round 2 calculations		
Time taken to change over (T9-T7)	time	
Time taken to light the stove (T10-T9)	time	
Time taken to char (T12-T10)	time	
Time taken for char to cool (T13-T12)	time	
Change Over 2		
Weight of canister and fuel	g	
Start weight of prepared fuel in change over 1 (W3)	g	
Start time to light the stove (T14)	time	
Time when fuel catches fire (T15)	time	
Start time to cook (T16)	time	
Finish time charring (T17)	time	
Time when char cools (T18)	time	
Weight of charcoal produced (C3)	g	
Weight of ash produced (S3)	g	
Gasifier round 3 calculations		
Time taken to change over (T14-T12)	time	
Time taken to light the stove (T15-T14)	time	
Time taken to char (T17-T15)	time	
Time taken for char to cool (T18-T17)	time	
SUMMARY		
Total time of cooking process (T6-...-T1)	min	
Total time to cook the meal (T6...-T3)	min	
Gross fuel used to char (W1+W2+...n)	g	
Total time to char	min	
Total fuel used while cooking	g	
Total char produced (C1+C2+...n)	g	
Total ash produced (S1+S2+...n)	g	
%char produced from fuel in charring (C1/W1*100)	%	
%char produced from fuel in charring 2 (C2/W2*100)	%	
Average %char (Charring 1+Charring 2)	%	
Net fuel consumption per test	g	
Average cooking time - change time	min	
Net fuel consumption per meal	g	
Time to light	min	

Data of Food Cooked				
	Dish 1:			
	Ingredient	**Amount (g)**	**Notes**	
1				
2				
3				
4				
5				
6				
7				
Weight of the pot (g)				
Weight of pot + dish 1 (g)				
Weight of the dish 1 (g)				
Time to cook dish 1 with gasifier (T4-T3)				
Time to cook dish 1 with 3stone fire (T22-T21)				
	Dish 2:			
	Ingredient	**Amount (g)**	**Notes**	
1	Tomatoes			
2	Kales			
3	Onions			
4	Cooking oil			
5	Salt			
6	Royco cubes			
7				
Weight of the pot (g)				
Weight of pot + dish 2 (g)				
Weight of the dish 2 (g)				
Time to cook dish 2 with gasifier (T6-T5)				
Time to cook dish 2 with 3stone fire (T24-T23)				
	Dish 3:			
	Ingredient	**Amount (g)**	**Notes**	
1				
2				
3				
4				
5				
6				
7				
Weight of the pot (g)				
Weight of pot + dish 1 (g)				
Weight of the dish 1 (g)				
Start cooking dish 3				
Time when dish 3 ready				
Time to cook dish 3 with gasifier				
Time to cook dish 3 with 3stone fire				

Temperature of flames (time)	C°	Hatch Position (Open/close)
Average temperature:		

Additional notes	Fuel	Moisture Content

Figure A. 2. *Template for field based cooking test*

Date:
Name of household:
Farm size:
Most frequent tree used/preferred for cooking fuel:

Biomass measurement
Species of wood pruned:
Date of pruning:
Weight of pruned (kg):

Species of wood pruned	Age of tree pruned	Date of pruning	Weight (kg)

Physical Counting

Name of tree	Age (years)		
	0 - 3	3 - 6	>6

Additional notes:

Figure A. 3. *Template for biomass observation*

Appendix B: Heat Characteristics

B.1. Heating values of Wood species identified in farms in Kwale, Kenya

Lower heating value (LHV) for woody biomass feedstocks in the farm and biochar produced during cooking are listed in Table B.1. Some of LHV were determined by using the following formula (WBCSD CSI, 2014)

$$LHV = HHV - 0.212H - 0.0245M - 0.008O \quad \text{(B.1.)}$$

with, H is hydrogen content, M is moisture content and O is oxygen content (Table B.2.)

Table B. 1. *Lower Heating Value (LHV) of wood species in Kwale*

Species (Binomial name)	LHV (MJ/kg)	Sources
Azadirachta indica	18.47	Own calculation
Casuarina equisetifolia	18.28	Own calculation
Mangifera indica	16.7	Velázquez-Martí et al. (2017)
Anacardium occidentale	18.87	Couto et al. (2014)
Leucaena leucocephala	18.55	Bunchan et al. (2017)
Melia azedarach	15.6	Own calculation
Senna siamea	18.4	Torres-Rojas et al. (2011)
Afzelia quanzensis	19.84	Guibal et al. (2017), p. 285
Annona muricata	18.4	Torres-Rojas et al. (2011)
Annona senegalensis	17.71	Erakhrumen et al. (2009)

Table B. 2. *HHV, H, M, and O values for calculating LHV*

Species	HHV (MJ/kg)	H (%)	M (%)	O (%)	Additional notes
A. indica	19.62[a]	3.42[b]	16.12	40.72[b]	Moisture content (M) average value during field observation
C. equisetifolie	20.29[a]	5.83[c]	17.07	43.36[c]	
M. azedarach	19.62[a]	3.42[b]	17.63	40.72[b]	Heating properties were assumed to be the same with *A. indica*. M value obtained during field observation

[a] Puri et al. (1994)
[b] Mensah et al. (2017)
[c] Duke (1983)

B.2. Specific heat of food ingredients for cooking

Specific heat (C_p) of food ingredients was used for determining the value of sensible heat during cooking, which later used to determine overall thermal efficiency of cookstoves.

Table B. 3. *Specific heat capacity of food ingredients (Engineering ToolBox, 2003)*

Ingredient	Heat Capacity (kJ/kg.degC)
Bean	1.17
Capsicum	3.81
Carrot	3.81
Coconut milk	3.98
Cooking oil	1.67
Cow milk	4.00
Dough	2.80
Fish	3.18
Garlic	3.31
Kale	3.73
Spinach	3.68
Maize flour	2.19
Margarine	1.67
Mung bean	1.17
Okra	3.68
Onion	3.77
Pasta	1.80
Potato	3.43
Salt	0.88
Sugar	1.24
Tomato	3.98
Tomato paste	3.98
Water	4.19

Appendix C: Results from Field Observation

C.1. Availability and need of fuel and energy

Table C. 1. *Comparison of availability and need of fuel (mass) and energy on all twelve households*

Household Farm	Biomass available (kg/hh/day)	Gross fuel consumption (kg/hh/day)		Energy available (MJ/hh/day)	Gross energy consumption (MJ/hh/day)	
		3-Stone open fire	TLUD Gasifier		3-Stone open fire	TLUD Gasifier
1	1.77	6.37	2.78	32.6	117	51.0
2	3.28	6.06	4.81	59.6	110	87.4
3	6.84		5.93	126		109
4	2.89	4.53	3.44	51.5	70.7	53.7
5	2.91		2.47	53.7		45.1
6	2.87		2.61	53.0		47.7
7	5.74	4.95	1.76	106	89.4	31.7
8	1.89		2.05	35.7		37.4
9	4.94		3.72	91.2		70.0
10	3.42		2.61	63.1		47.8
11	1.25		2.36	22.2		45.3
12	3.90		2.49	69.5		42.7

C.2. KPT results

HH: Household

Table C. 2. *KPT results per dinner meal when cooking with three-stone open fire*

Parameter	Unit	HH 1	HH 2	HH 4	HH 7
Fuel consumption	kg/hh	2.12	2.02	1.51	1.65
Fuel consumption	kg/capita	0.35	0.29	0.25	0.41
Efficiency	%	8%	10%	13%	4%
Energy consumption	MJ/capita	6.49	5.24	3.93	7.45
Energy delivered to pot	MJ/capita	0.52	0.52	0.51	0.30

Table C. 3. *KPT results per dinner meal when cooking with The Gastov*

Parameter	**Unit**	**HH 1**	**HH 2**	**HH 3**	**HH 4**	**HH 5**	**HH 6**	**HH 7**	**HH 8**	**HH 9**	**HH 10**	**HH 11**	**HH 12**
Fuel consumption	kg/hh	0.93	1.60	1.98	1.15	0.82	0.87	0.59	0.68	1.24	0.87	0.78	0.83
Fuel consumption	kg/capita	0.15	0.25	0.51	0.18	0.11	0.12	0.12	0.08	0.50	0.12	0.33	0.27
Efficiency	%	21%	13%	8%	21%	13%	19%	15%	20%	12%	16%	42%	12%
Energy consumption	MJ/capita	2.72	4.49	9.42	2.83	2.07	2.25	2.16	1.46	9.40	2.13	6.29	4.57
Energy delivered to pot	MJ/capita	0.57	0.58	0.75	0.59	0.27	0.43	0.32	0.29	1.13	0.34	2.64	0.55
Charcoal produced	kg/capita	0.03	0.05	0.10	0.03	0.04	0.03	0.04	0.08	0.16	0.04	0.08	0.06

Appendix D: LCA

D.1. Characterisation factors

Table D. 1. *Characterisation factors for both Set 1 and Set 2 from non-renewable biomass (NRB) adapted from Sieber (2016)*

Pollutant	Pollutant group	GWP100	GWP20
CO_2	Kyoto gasses	1	1
CH_4	Kyoto gasses	36	87
N_2O	Kyoto gasses	298	268
CO_2	Ozone precursors	4.98	18.6
NMHCs	Ozone precursors	4.23	14
BC	Aerosols and precursors	846	3200
OC	Aerosols and precursors	-43.24	-160
SO_2	Aerosols and precursors	-71.44	-140
RB-credit	Carbon credits	-1	-1
Biochar credit	Carbon credits	0	0

Table D. 2. *Characterisation factors for Kyoto Gasses only (Set 1) from renewable biomass (RB)*

Pollutant	Pollutant group	GWP100	GWP20
CO_2	Kyoto gasses	0	0
CH_4	Kyoto gasses	34	86
N_2O	Kyoto gasses	298	268
Biochar credit	Carbon credits	-1	-1

D.1. Climate change impacts (kgCO_2-eq)

Table D. 3. *Climate change impacts of all twelve households in Waa Ward, Kwale County*

	Climate change impact (kg CO_2eq)							
	GWP 100 Set 1		GWP100 Set 2		GWP20 Set 1		GWP20 Set 2	
	Reference	Improved	Reference	Improved	Reference	Improved	Reference	Improved
Household 1	0.202	-0.062	0.202	-0.061	0.141	-0.048	0.864	0.024
Household 2	0.149	-0.139	0.149	-0.139	0.081	-0.166	0.613	0.184
Household 3		-0.223		-0.222	0.057	-0.165		0.073
Household 4	0.257	-0.029	0.257	-0.028	0.134	-0.038	1.063	0.090
Household 5		-0.035		-0.030		-0.027		0.010
Household 6		0.075		0.153		0.083		0.446
Household 7	0.421	-0.019	0.421	-0.019	0.221	-0.026	1.744	0.059
Household 8		-0.172		-0.160		-0.164		-0.107
Household 9		-0.328		-0.258		-0.285		0.069
Household 10		0.033		0.144		0.041		0.422
Household 11		-0.156		-0.110		-0.128		0.206
Household 12		-0.113		-0.076		-0.091		0.099

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