Biochar: Properties and Potential Benefits for Agricultural Soil in Rwanda

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Biochar: Properties and potential benefits for agricultural soil in Rwanda

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Abstract

Physical and chemical soil degradation is becoming a major challenge for agricultural productivity in Rwanda, which is the most important part of the country's economy. The wide spreading soil degradation in Rwanda is mainly a result of naturally poor soils coupled with unsustainable soil management leading to, for example, accelerated soil erosion, acidification, nutrient loss, compaction, and to decreasing yields. Biochar, as an end product of pyrolysis of biomass in the absence of oxygen, has been proposed as a soil amendment in remediation strategies because of its positive effects on soil productivity relevant parameters such as soil pH, structure, nutrient retention, water holding capacity, and carbon storage.

This thesis reviews existing scientific literature on Rwanda's soil characteristics, biochar properties, different types of biochar feedstock specific to Rwanda, and potential benefits of biochar application to the soil in Rwanda. Because there are no published data on biochar application in Rwanda's soil, biochar data from soils with similar properties to soil in Rwanda were used. Biochar production strategies were also reviewed including large-scale production, mainly used in industries, and small-scale production, primarily used on farms.

The thesis revealed that temperature and type of feedstock used in biochar production are among the most crucial parameters that determine the properties of produced biochar. High pyrolysis temperature promotes biochar production with high porosity, organic carbon content and pH. biochar produced from solid wastes and animal manure feedstock exhibit properties with high CEC and low carbon content while biochar produced from wood and crop residue exhibit properties of high carbon content, surface area and porosity

The research clearly showed that biochar application improved soil with similar properties and fertility issues to soil in Rwanda and that biochar produced with feedstock widely available in Rwanda would have ideal properties, hence increasing crop yield when apply to the soil.

Keywords: biochar, Rwanda, soil, agriculture, biochar application, soil quality, benefits of biochar.

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1. Introduction

Rwanda is a landlocked country in the east-central part of Africa, with an estimated population of 13 million people and a surface area of 26.338 km^2. Rwanda's climate is tropical temperate because of the high altitude. The average annual temperature ranges between 16°C and 20°C; and has significant rainfall of about 45 inches annually concentrated in two rainy seasons. Rwanda has a hilly, mountainous relief and naturally fragile soil generated by the physical-chemical weathering of gneiss, granite, and volcanic rocks, which make up the superficial geology of Rwanda (Twagiramungu, 2006). Rwanda's soils can be categorized into nine main soil orders (Figure 1).

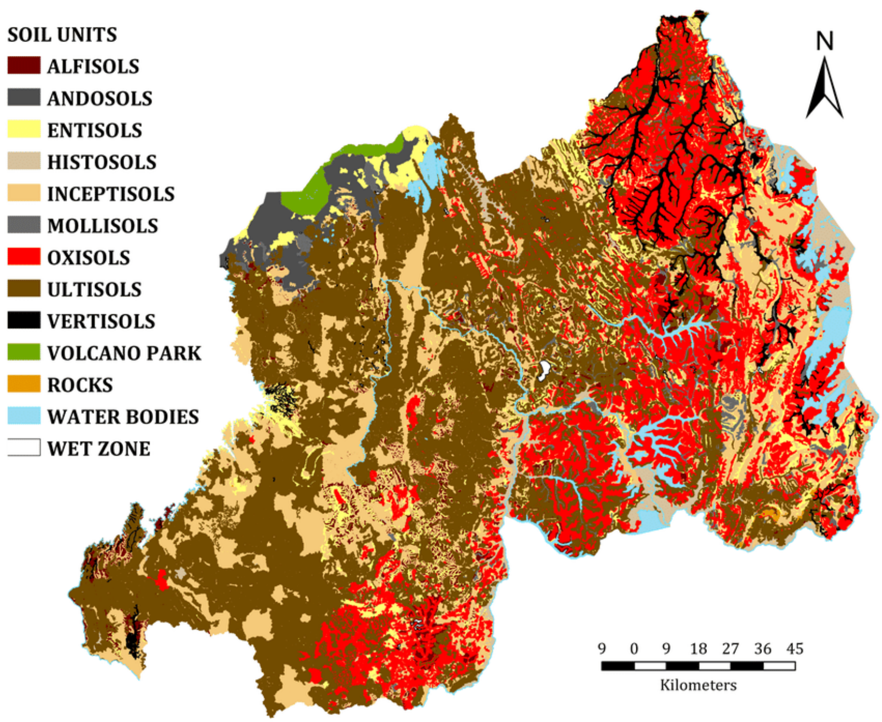

Figure 1: Rwanda soil orders classified using USDA soil taxonomy (Nzeyimana et al., 2014)

Cropland makes up 1.4 million hectares or 52% of the total area of the country. The agricultural sector contributed 32.6% to the national gross domestic product (GDP) in 2007 and was projected to contribute 33% to the GDP in 2020. However, issues like nutrient depletion, inadequate ways to retain soil moisture, soil acidity, improper use of soil fertilizers, and soil erosion are stress factors on soil fertility and agriculture production in Rwanda (Minecofin, 2012).

Historically application of manure to agricultural soil has been the primary method used to counteract these challenges and to restore degraded soil in Rwanda (Kim et al., 2013). However, the benefits of manure application vary because of variations in quality and degradation during storage and processing (Giller et al., 1997). Under Rwandan conditions, animal diets are also often poor, which lowers the nutrient content of manure (Bayu et al., 2005). The high cost of manure handling, poor construction of cowsheds and other animal shelters hinder farmers from appropriately using the recommended manure management practice (Kim et al., 2013). Manure also needs to be applied annually because of microbial decomposition processes (Ndambi et al., 2019).

Biochar, a charcoal-like material and carbon-rich soil amendment that is produced by heating materials like grass, crop residues, rice hulls in absence of oxygen has been proposed as a soil amendment to sustain and remediate a degraded soil (Lehmann et al., 2012). Biochar application has shown to improve soil properties include cation exchange capacity, surface area, pH, soil structure and increase the crop yield. Addition of biochar to the agricultural soil in Rwanda might improve soil properties because of its consistent production method and long-lasting stability in the soil which require an application only in 10 to 50 years depending on the amounts applied (Greenberg et al., 2019).

This thesis explores the properties of soil in Rwanda and potential benefits of biochar application. Specific objectives include (1) a review of properties and limitations of Rwanda's soil, (2) a review of biochar properties and production methods, and (3) identification the potential benefits of biochar to soil in Rwanda and available feedstocks for biochar production in Rwanda.

2. Material and Methods

Literature review is the primary method of data collection for this thesis. I used articles that specify the properties of biochar produced under varying conditions including biochar as produced at low (<500 °C) and high (>500 °C) temperature and as derived from different feedstock including hardwood, switchgrass or rice hulls. The main properties of interest were pH, carbon content, bulk density, porosity, and cation exchange capacity of biochar because these properties are in critical need for improvement in most agricultural soil of Rwanda.

The literature review also included a systematic overview of soil properties and limitations in Rwanda. The parameters that were analyzed were limited to soil pH, cation exchange capacity, bulk density and porosity, soil organic matter, and soil organic carbon. I focused on the parameters stated above and analyzed the effect of biochar to soil that has similar properties to soil in Rwanda. Databases used for this literature reviews included ScienceDirect, Google Scholar, Web of Science, Research gate, PubMed, and International Biochar Initiative, Rwanda Agricultural Board, Rwanda Soil Information Services and National Institute of Statistics. The review included published papers between the 1980s up to 2021.

3. Properties of Agricultural Soil in Rwanda

Soil health is the foundation of sustainable farming practices as fertile soil provides the essential nutrients plants need for growth. The following section outlines some of crucial properties of Rwanda's soil that are often targeted for remediation including pH, cation exchange capacity, bulk density, porosity, and organic matter which allows water and air to infiltrate, plants and roots to grow, biota to thrive.

3.1. Soil pH

Soil pH determines the acidity and basicity of the soil where soil with pH below 7 is acidic while pH above 7 is categorized as basic or alkaline (Thomas, 2018). Low soil pH can lead to soil problems including reduction of microbial and other plant nutrients. Acidic soil accounts for up to 50% of the world's arable soil and is widespread, especially in tropical and subtropical countries where agricultural production is under severe stress because of poor farming practices, nutrient deficiencies, high population growth, and limited financial resources (Najafian et al., 2012). In Rwanda, it is estimated that two-thirds of the cultivated soil is acidic showing increased concentrations of exchangeable aluminum ions (Crawford et al., 2008).

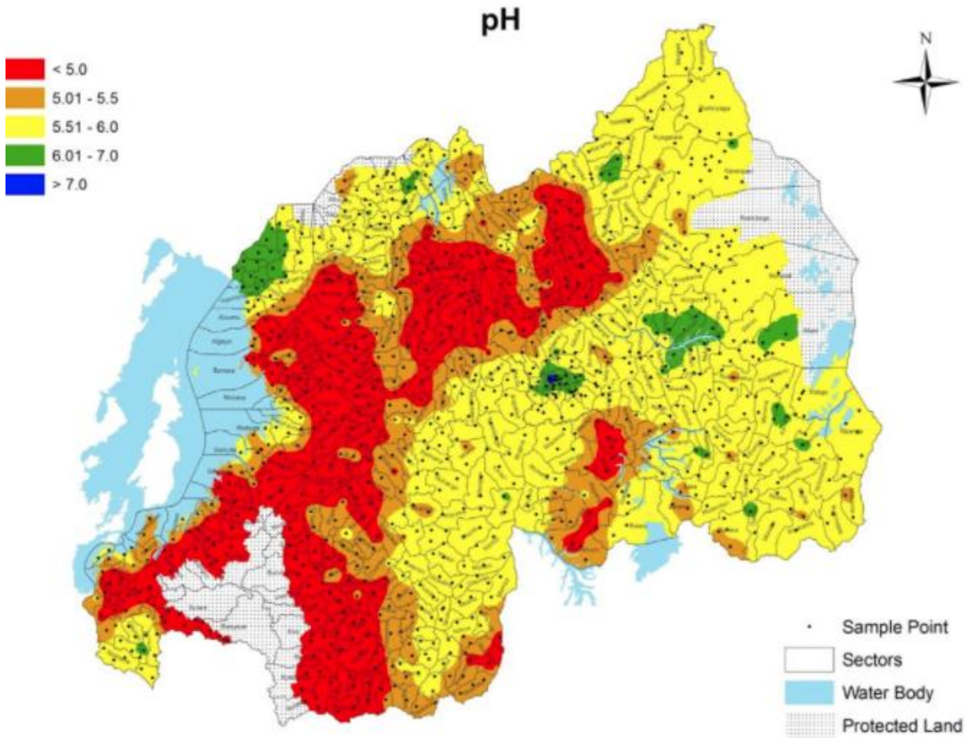

Figure 1. pH of soil in Rwanda sorted by provinces (east, north, south, west) (International Fertilizer Development Center, 2020).

Poor crop growth in acidic soil is correlated directly with aluminum concentration Aluminum is present in all soil, however, as the soil pH decreases below 5, the concentration of aluminum becomes increasingly toxic for most major crop species (Rout et al., 2001). Aluminum interferes with cell division in root tips and lateral roots, increases the cell wall rigidity, reduces the DNA replication by increasing the rigidity of the DNA double helix, fixes phosphorus in less available forms in the soil, decreases soil respiration, and interferes with enzymes activities (Kochian et al., 2015). Acidic soil with pH less than 5 with increased aluminum concentration and deficits in calcium and magnesium dominate mostly in the western part of Rwanda (Adewole et al., 2008). Besides negative effects on root development, in soil with pH less than 5, both organic matter mineralization and nitrogen transformation are severely reduced because of negative effects on the soil microbial community (Bergamasco et al., 2019). Essential plant nutrients such as potassium, calcium, magnesium or molybdenum are deficient in acidic soil as well (Crawford et al., 2008).

3.2 Cation exchange capacity

Soil cation exchange is the ability of the soil to retain and release cations, which are held temporarily by negatively charged surfaces of clay particles and organic matter through electrostatic forces (Astela et al., 2010). Cation exchange capacity (CEC) is an important chemical property of agricultural soil, which reflects the total amount of negatively charged surfaces contributing to the retention and supply of cations in general and cationic plant nutrients such as Ca^{2+}, Mg^{2+}, NH_4^+, and K^+ (Astela et al., 2010). However, soil CEC in Rwanda particularly in the northern and western parts is very low and ranges between 0-10 cmolc/kg

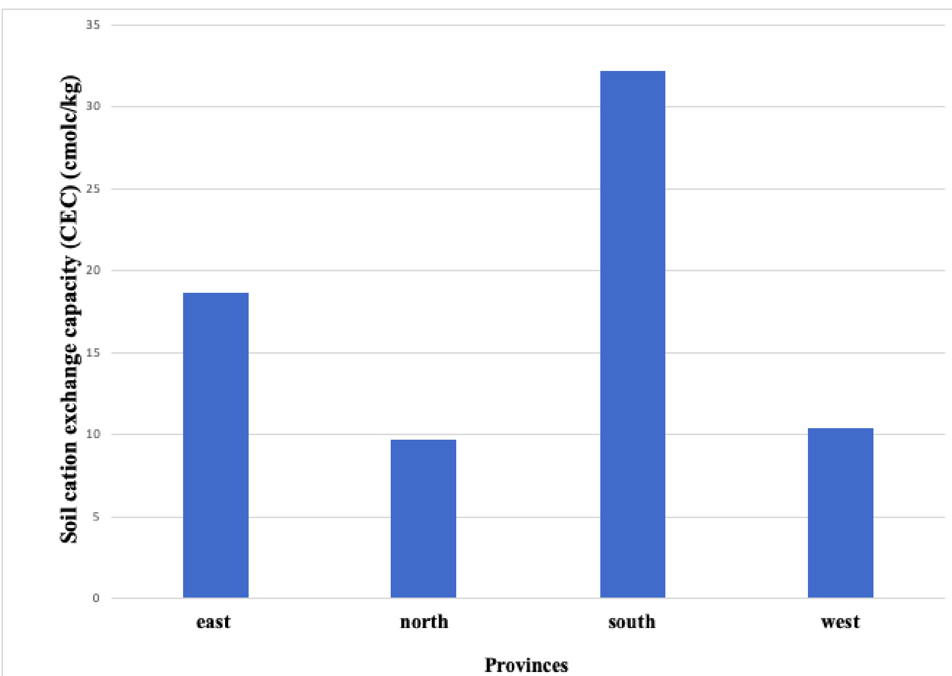

Figure 2. Average soil cation exchange capacity of Rwanda is sorted by the provinces. North and west provinces show the lowest cation exchange capacity (Schnable Lab, 2019)

The soil CEC is proportion to the amount and type of clay and organic matter content in the soil, therefore affect soil fertility.(Tan et al., 1984). The low CEC of soil in Rwanda can be attributed to the abundance of highly weathered clay minerals such as kaolinite and sandy soil texture which has low organic matter content (Uwitonze, 2016).

3.3 Bulk density and porosity

Soil bulk density and porosity are indicators for soil quality influenced by both physical and chemical properties of the soil including organic matter content, texture, and structure or aggregation (Arvidsson, 1998). Porosity refers to the fraction of the total soil volume that is taken up by the pore space, which facilitates the availability and movement of water and air within the soil (Ramesh et al., 2019). Bulk density is the mass of dry soil per unit of bulk (Sauzet et al., 2021). Soil bulk density is inversely proportioned to the soil porosity, the greater the porosity, the lower the bulk density. Clay soil bulk density ranges between 1.0-1.6 g/cm^3, while bulk densities for sandy soil range between 1.2-1.8 g/cm^3 (Rivenshield & Bassuk, 2004). The average soil bulk density in all provinces of Rwanda is remarkably high ranging between 1.5-1.60 g/cm^3 in cultivated soil because cultivation lowers soil organic matter and weakens the stability of soil aggregates rendering them susceptible to disintegration (Bizuhoraho et al., 2018).

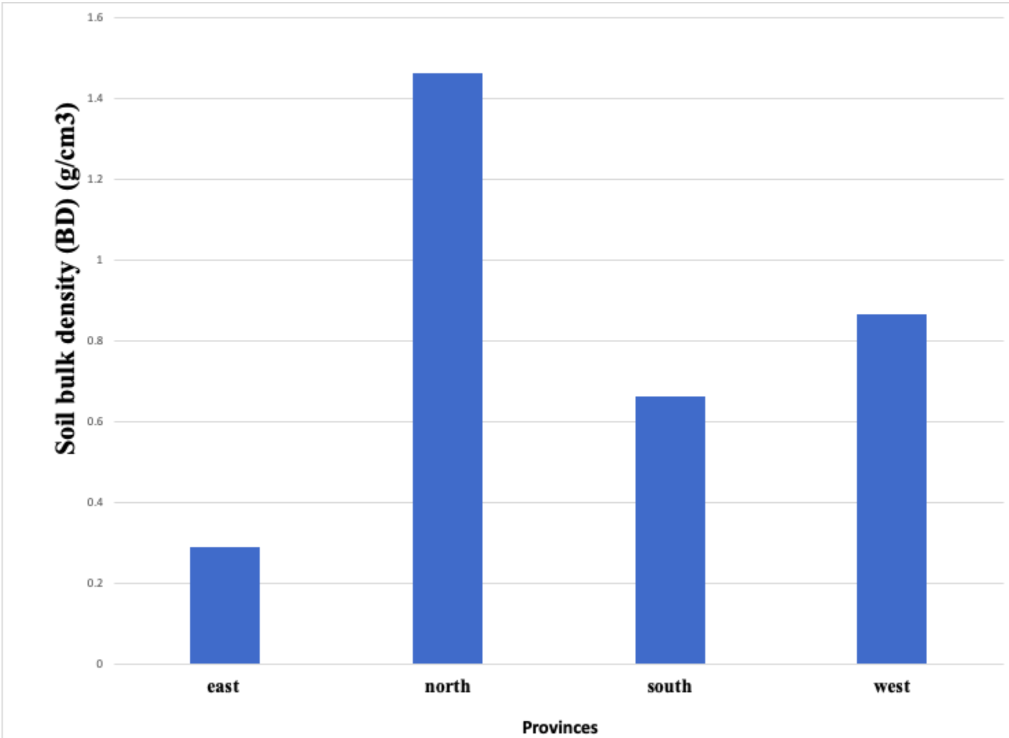

Figure 3. Average soil bulk density of Rwanda sorted by provinces. South and east provinces show highest bulk density (Schnable Lab, 2019).

Soil with a high proportion of solids to pore space has higher bulk densities. Both porosity and bulk density are useful in indicating soil compaction because compacted soils have particles arranged near eachother which lead to high bulk density and low porosity of the soil (Singh & Sainju, 2018). Rwanda's cultivated soils have the average bulk density range between 1.5-1.6 g/cm^3 in all provinces of the country. This is because cultivation increase the soil bulk density by reducing soil organic matter, increasing soil compaction, and weakening the stability of soil aggregate rendering them susceptible to disintegration (Bizubuhoro et al., 2018). High soil bulk density and low porosity hinders the root growth and movement of water and air , hence reduce crop yield and vegetative cover available to protect soil from erosion (Bizuhoraho et al., 2018).

3.4 Soil organic matter and soil organic carbon.

Soil organic matter (SOM) is the fraction of the soil that consists of plants and animal tissues in various stages of decomposition. The amount of organic matter in mineral soil ranges from very low being (1%) by weight, average being (2-4%) and high being greater than (5%). SOM is the largest reservoir of organic carbon in soil, stores essential soil nutrients and is critical factor for soil aggregate formation and stability (Johnston et al., 2009). Soil organic carbon (SOC) refers to the carbon components of organic compounds in the soil and is a measurable component of SOM (Schjønning et al., 2018). SOC is major indicator of soil fertility in the tropics, a study in Uganda which conducted on ferralsol to explore the critical range of SOC concentration and associated fraction for optimal crop yield response concluded that the overall critical concentration range of SOC for high yield is 1.9-2.2%, which corresponds to 3.5-5.0 g kg-1 for sandy soil and 9-11g kg-1 for clay soil (Musinguzi et al., 2016). In general, the SOC content depends on soil mineral characteristics, climate, above-ground and below-ground carbon input, and soil management intensity and disturbance (REF). Soils in Rwanda usually show low SOC contents mainly due to low soil clay and silt contents, erosion, and accelerated decomposition due to farming. The SOC content positively affects both physical and chemical properties of the soil such as water infiltration and water holding capacity, nutrient availability, and activity of microorganisms (Schjønning et al., 2018). A reduction in SOC also leads to an increase in the bulk density and decrease in CEC (Yost et al., 2019). Generally speaking, as higher the SOM or SOC content as better are the conditions for sustainable crop production in the long-term.

4. Biochar

Biochar is a carbon-rich organic material and is produced by the pyrolysis of biomass in the absence of oxygen under limited oxygen conditions (Das et al., 2021). While production of biochar is similar to charcoal production. Biochar is primarily produced to be employed as a soil additive while charcoal is employed in energy production. (Verheijen et al., 2010). Biochar exhibits high organic carbon content and contains macro-and micronutrients including phosphorus, calcium, magnesium, and nitrogen (Rawat et al., 2019). Biochar is generally characterized by a high specific surface area, high pH, and high porosity with pores sizes from micro- to macro-pores. The micro and mesopores are critical for water storage and retention and the pores are biologically important because they provide habitats for microorganisms (Tomczky et al., 2020).

5. Biochar production

Biochar is produced from fast or slow pyrolysis of biomass with little or no oxygen present in kilns and furnaces (Lehmann et al., 2011 & Lorenzi et al., 2018). Fast pyrolysis employs 6 different steps including pre-treatment, pyrolysis, solid removal, oil recovery, and heat regeneration. slow pyrolysis has 4 steps to generate biochar which are pre-treatment, pyrolysis, solid removal, and heat regeneration (Yuan et al., 2020). Slow pyrolysis is robust and energy efficient process which is widely used for farm based or small-scale biochar production . The temperature range for slow pyrolysis is 300°C - 500°C and low heating rate of 0.1-10°C min^{-1} which removes the vapors during the heating process , therefore generate biochar yield between 20-60% (Brown et al., 2010, El-Nagaar et al., 2019). In fast pyrolysis the biomass is heated rapidly at temperature above 500°C and 10-10000 $^{\circ}$C min^{-1} heating rate which generate 10-30% biochar yield. Fast pyrolysis decrease biochar yield because the biomass are heated rapidly and the pyrolysis vapors are rapidly released and transported from the vapor reactor which reduce the carbon deposition (Brown et al., 2010, El-Nagaar et al., 2019). There are distinctive designs, which use different pyrolysis units to produce biochar, for instance, bed pyrolizer, which is common in Japan to convert rice husks and sawdust to biochar. Pacific pyrolysis (Figure 3) is another design that has a series of paddles inside to move biomass over the hot surface of the kiln. The pacific design can be tailored to produce a range of several types of biochar with using either fast or slow pyrolysis(Joseph &Taylor, 2014).

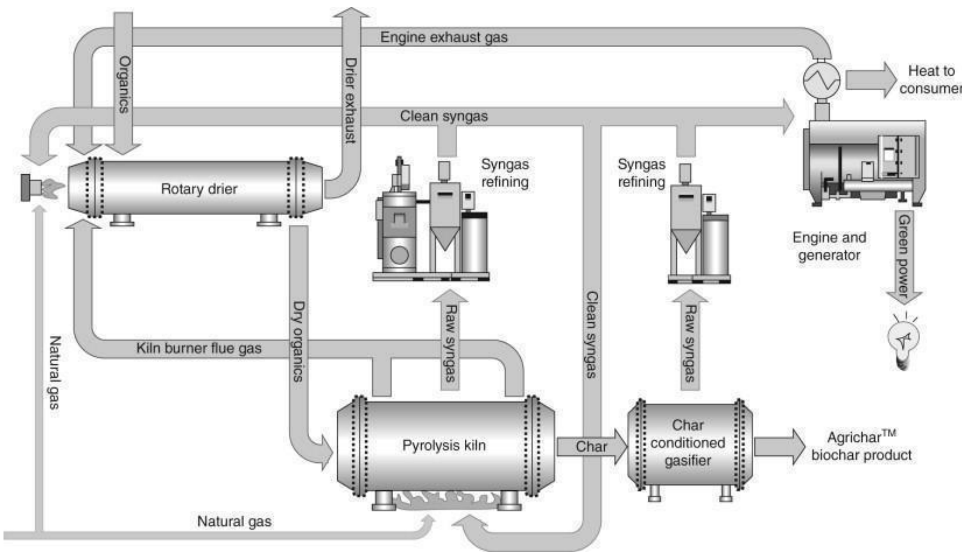

Figure 4. Pacific pyrolysis unit which is used to produce different types of biochar on large scale (Joseph & Tylor, 2014)

Biochar production on small scale is mainly done by using kilns and retort methods.The small scale production methods include air free two chambers designs where the sealed inner chamber filled with biomass, and the outer chamber which act as an insulator surrounding the inner cylinder. A top lit updraft gasifier (Figure 4b) is another design that is constructed from cylindrical containers used to produce biochar on a small scale where biomass is placed in a container with holes on the base as the main source of air. (Tryner et al., 2014).

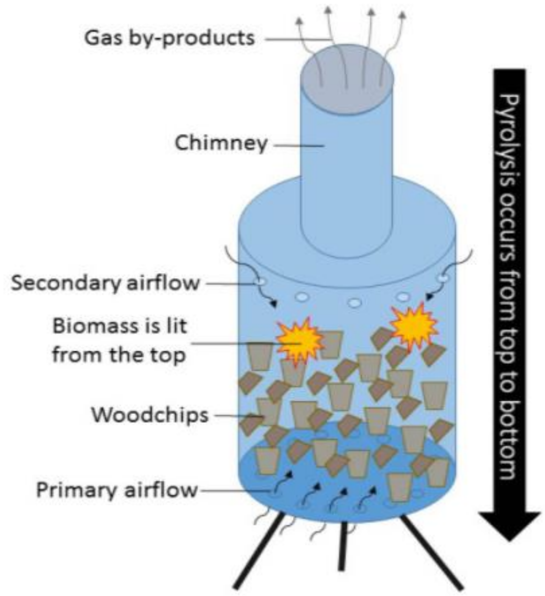

Figure 4a. Retort kiln design based on two-chamber, the inner cylinder filled with wood sand outer chamber surrounding the inner cylinder as an insulator. 4b. Top lift up-draft gasifier model constructed from cylindrical containers. They produce high quality biochar with less feedstock (Nebraska Forest services, 2012).

6. Biochar properties compared to properties of soil in Rwanda

Biochar exhibits desirable properties to improve soil characteristics relevant to production in agricultural soil including cation exchange capacity, specific surface area, pH, bulk density, carbon and nitrogen content, organic matter, and porosity. Characteristics of biochar are influenced by factors such as pyrolysis temperature and the type of feedstock used (Ippolito et al., 2020). The initial properties of feedstock used in biochar production play a critical role in determining the characteristics of produced biochar. For instance, biochar derived from wood contains the most carbon content out of biochar feedstocks but has lower available nutrients, while manure-derived biochar contains lower carbon content and high available nutrients

(Ippolito et al., 2020). Biochar derived from other feedstocks, including grass-based tend to have properties somewhere between these two extremes (Ippolito et al., 2015). Pyrolysis temperature also plays a critical role in the determining the properties of produced biochar: it is attributed to the evaporation of moisture, light volatile organics and degradation of plant biomass building units such as cellulose or lignin (Figure 5). As pyrolysis temperature increases, biochar carbon content, ash content, pH, and surface area increase while nitrogen, hydrogen, and decrease oxygen content (Nguyen et al., 2017).

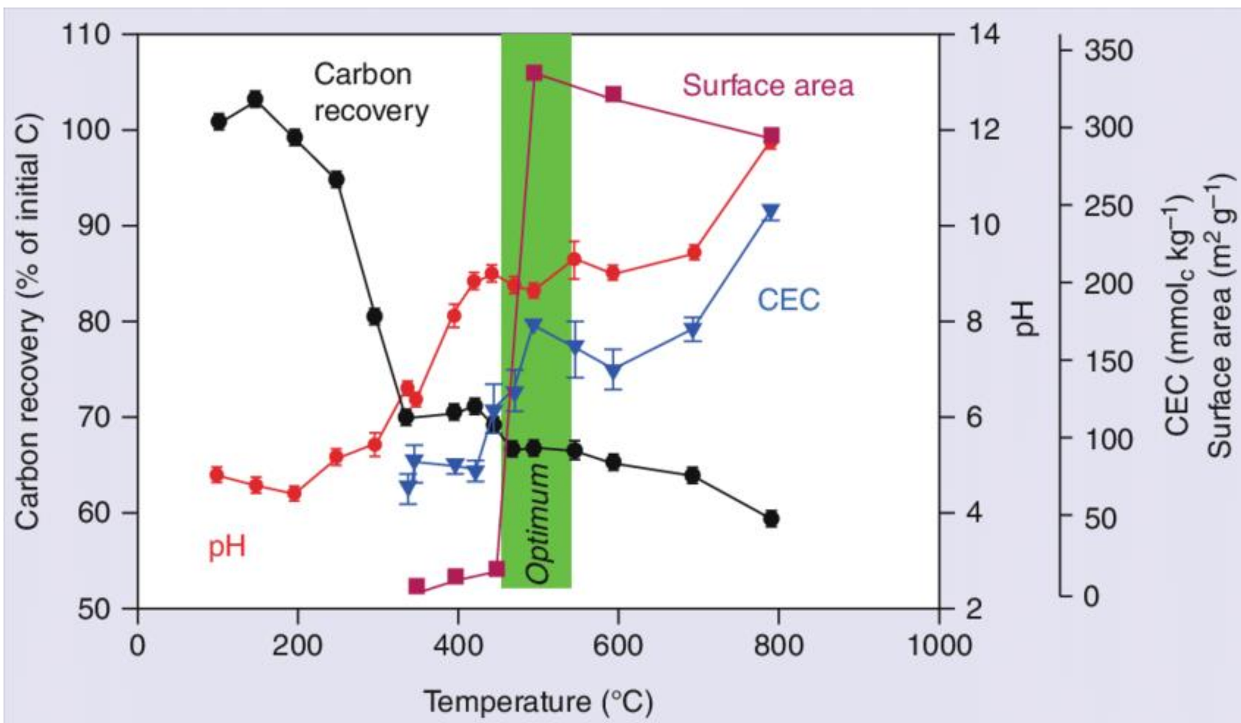

Figure 5. Effect of pyrolysis temperature on biochar properties derived from wood. The optimum temperature to produce high-quality char is around 500°C (Lehmann, 2007).

6.1 Biochar pH compared to pH of soil in Rwanda

Biochar pH must be taken into consideration if biochar is used as a soil amendment because it can impact overall soil pH, and because the strongly alkaline pH is usually above pH values observed in most alkaline soils (Zhang et al., 2019). During pyrolysis, acidic functional groups are removed and the concentration alkali salts and alkaline earth elements become enriched (Lehman et al., 2011). These salts include readily soluble salts, carbonates, and soluble metal oxides, and hydroxides (El-Naggar et al., 2019). Biochar produced under high temperatures (above 500°C) are likely to have higher pH than biochar produced below 500°C from the same feedstock because more acidic groups are removed (Zhang et al., 2021).Generally the pH of biochar is usually found to be higher than 7 while the pH of most soil in Rwanda is less than 6.

6.2 Biochar cation exchange capacity compared to cation exchange capacity of most coarse and sandy soil in Rwanda

The cation exchange capacity (CEC) of biochar indicates the capacity of biochar to adsorb and release cationic nutrients (Tomczyk et al., 2020). CEC depends on the type of feedstock used in biochar production. For instance, the CEC of biochar produced at 500°C from pig manure (32.7 cmol/kg) is lower than biochar produced from chicken manure (81.4 cmolc/kg) (Zhang et al., 2021). Biomass with a high ash content will produce biochar with higher CEC because alkali and alkali metals in biomass promote the formation of oxidized functional groups which are the surface groups that carry negative charge in biochar (Tomczyk et al., 2020).

Additionally, CEC decreases with pyrolysis temperature due to dehydration and deoxygenated of biomass which reduce the functional groups (Zhao et al., 2020). For instance, the CEC of biochar from apple branches tree significantly decreased from 66.6 cmolc/kg to 18.5 cmolc/kg as pyrolysis temperature increased from 300 to 600°C (Zhao et al., 2017). Biochar is also known to have high surface and negative charge on its surface which are properties that make biochar capable of increasing the soil CECE(Liang et al., 2006). As the surface area increase by increasing the pyrolysis temperature, the CEC will increase as well , therefore more area for negatively charge sites (Liang et al., 2006).In short, the average cation exchange capacity of biochar is usually range between 14-50cmolc/kg while the average cation exchange capacity of course and sandy soil in Rwanda ranges between 1-10cmolc/kg.

6.3. Bulk density and porosity of biochar compared with soil in Rwanda

The bulk density refers to the unit of volume of collected particles,; while porosity is a measure of the percentage of empty space in biochar or soil (Biochar International., 2012). Both bulk density and porosity of biochar are influenced by the feedstock and pyrolysis temperature used in the production process. Biochar's-produced at higher temperatures seem to exhibit more porosity with less dependency on the type of feedstock, Biochars produced at higher temperatures will exhibit more porosity, regardless on most types of feedstock (figure 6a and 6b). BD of biochar mostly ranges between 0.06 - 0.6 g/cm^3 with (moat feedstock), 0.12 - 0.17 g/cm^3 for (pine sawdust) and (pea straw) produced at pyrolysis temperature of > 500C (Askeland et al., 2019).Woody biochar will have high porosity and low bulk density <0.6 g/cm^3 compared to ash biochar which has low porosity this is because tars and minerals found in high ash biochars block the pores (Brewer et al., 2014).

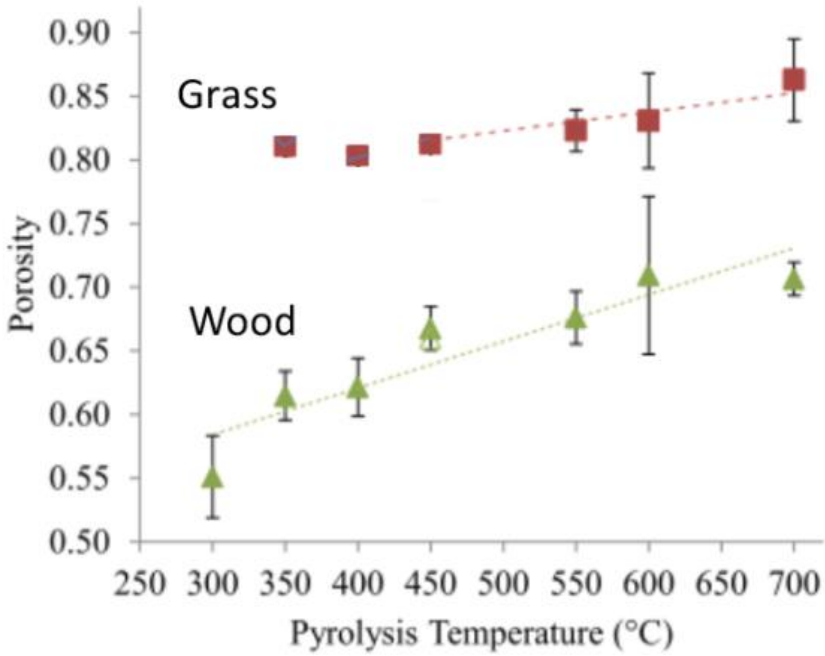

Figure 6a. Effect of pyrolysis temperature on porosity of biochar produced from different feedstocks. (Biochar International., 2012)

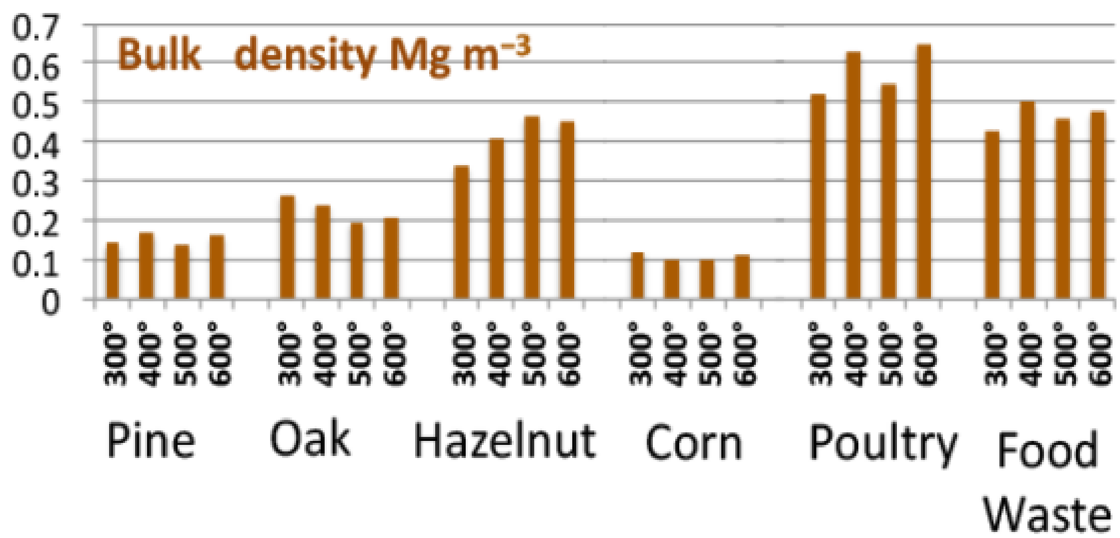

Figure 6b. Effect of pyrolysis temperature on bulk density from biochar produced from different feedstocks at different temperatures. (Biochar International, 2022)

6.4 Biochar organic content compared to soil in Rwanda.

Carbon is a primary element in condensed aromatic structures, which dominates the organic phase of biochar, therefore, biochar comprises between 65-90% of carbon, which can be sequestered in the soil in the long-term (i.e. >100 years). This is because compounds found in biochar are not as readily decomposed by soil microorganisms as organic material that is not pyrolyzed (Wijitkosum et al., 2019). The carbon content of biochar is determined by the pyrolysis temperature and type of feedstock used during production (Kim et al., 2013). For instance, at a 450°C pyrolysis temperature, the maximum carbon content in biochar produced from cattle and swine manure feedstock ranges between 16-38.27%, because of the low pyrolysis temperature used in production that did not allow the carbon to concentrate in feedstock while the total carbon in biochar produced from soybean and corn straw feedstock ranges between 65-70% at pyrolysis temperature above 500 °C (Sarfaraz et al., 2020). The addition of biochar to soil in Rwanda could also stimulate carbon sequestration processes, which would result in further co-benefits such as increased beyond the carbon added in form of biochar (Tomczyk et al., 2020).

7. Potential benefits of biochar application to soil in Rwanda

Biochar interacts with clay, silt, and soil organic matter in combination with feedstock and pyrolysis temperature controlled characteristics, determines the impact of biochar on soil properties (Zhu et al., 2017). Application of biochar can have positive impacts on properties of soil in Rwanda including CEC, bulk density, soil structure, organic carbon, crop yield and soil pH. The following section highlights the potential benefits of biochar amendments for soil properties in Rwanda.

7.1 Reduction of soil acidity through biochar application.

The pH of biochar ranges from 7 to 12, and its basic properties directly affect the soil after its application. Biochar is basic and contains varying concentration of alkaline cations and anions that is added into the soil as Ca, Mg, K, hydroxides and Carbonates. Because these components are water-soluble, they are able to ameliorate soil acidity throughout the soil profile (Shetty et al., 2020). The amendment of biochar to acidic soil reduces the acidity from average pH of 4.0 to the pH above 7, in turn, enhances plant growth by increasing soil fertility. Biochar produced from cacao shell, rice husk, wood feedstock at 300 °C pyrolysis temperature was added to an acidic soil in Indonesia (This soil in similar to Rwanda's and the feedstock is similar to those available in Rwanda). The result sowed a significant increase of pH in biochar added soil from 4.7 to 8.5 (Martinsen et al., 2015). The 10 years application of biochar in tropical regions of Kenya in Sub-Saharan Africa at the rate of 50 + 50 Mg ha−1 during the first two years showed slightly increase of soil pH from 4 to 7 and significantly increased during following years (Kätterer et al., 2019). These soils have similar properties to soil in Rwanda, meaning that long term (2-10 years) biochar application at the rate above 50 + 50 Mg ha−1 would significantly reduce soil acidity and increase the crop yield.

7.2 Increase soil cation exchange capacity through biochar application

Biochar is principally recalcitrant and contains organic functional groups that increase the soil CEC. Biochar with higher CEC has greater impact on soil CEC after application, for instance, the application of ash biochar will have more impact on soil CEC than the application of wood biochar because ash biochars usually have higher CEC than wood biochars (Hailegnaw et al., 2019).The application ($30\ t\ ha^{-1)}$ of coffee husk biochar produced at 350 °C to degraded sandy loam soil in Nigeria doubled the soil CEC from 19.1 to 40.4 $cmol_c\ kg^{-1}$ (Adekiya et al., 2020).

The soil in Rwanda, especially in northern and western regions, shows lower CEC ranges from 0-10 $cmol_c\ kg^{-1}$. This is because these soils are derived from highly weathered minerals such as kaolinite and low organic matter content (Uwitonze, 2016). Biochar amendment will increase the CEC in these areas of Rwanda, which will help with increase the soil clay content and fertility.

7.3 Biochar application decreases bulk density and increases soil porosity.

In addition to the improvements of soil chemical parameters, biochar can also improve several soil physical properties including bulk density, soil porosity and soil aeration (Blanco-Canqui, 2017). On average, application in tropical sandy soil of Brazil (which is similar to Rwanda's sandy soil) reduces the bulk density by 12% and this decreases as the rate of biochar applied increases (figure 7)

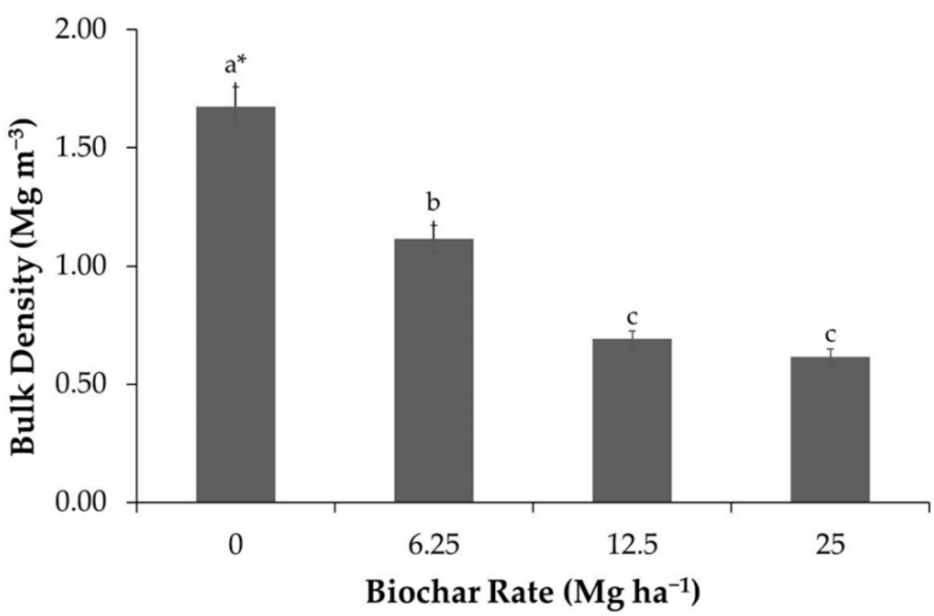

Figure 7. Soil bulk density as a function of biochar application rates (0, 6.25, 12.5, and 25 Mg ha−1) evaluated between 50-150 days after the application (Lustosa Carvalho et al., 2020)

Change in soil bulk density after application of biochar directly increases soil porosity. Chang et al. (2021) showed that biochar increased porosity by an average of 8.4%, with a larger effect in coarse textured soil than fine textured soil (Chang et al., 2021). On average Rwanda's soil is sandy and coarse with a high average bulk density ranging between 1.5-1.6 g cm^{-3}. This hinders root growth, water and air movement in the soil and weakens soil aggregates (Bizubuhoro et al., 2018). Addition of biochar to soil in Rwanda could significantly reduce bulk density by the average of 12% and increase porosity by 8% in average. Downstream effects of increasing soil porosity and reducing bulk density include positive implications for the water, heat, gases movement in the soil and therefore increase plants growth (Blanco-Canqui, 2017).

7.4 Soil structure improvement due to biochar addition.

Biochar affects soil aggregation by altering the soil pH and the aromatic compounds introduced in biochar and increase the organic matter which are both essential factors for soil aggregate formation (Wang et al., 2017).. Aromatic carbon structures in biochar improves soil aggregation by helping to bind biochar, native soil organic matter, and mineral particles thereby improving soil aggregate resistance against disruption by water and making the structure more resistant to physical disturbance (Noval et al., 2009). For instance the application (10-15 t ha-1 year-1) of biochar from local agricultural wastes on sandy soil in farmers field in Thailand where biochar has been used for over 3 years showed an increase of 6 to 25% average size of aggregate and wet aggregate stability (Prakongkep et al., 2020). The application of biochar to sandy and clay soil showed an increased aggregate stability by 4 to 8% when rate of biochar applied ranged between 0.1 and 10%. The aggregation increased as the amount of biochar added increased (Blanco-Canqui et al., 2017). When biochar enhances the soil aggregation, it provides the organic binding agents and stimulates growth of fungi that produces abundant hyphae that binds to soil particles ((Blanco-Canqui et al., 2017)

7.5 Biochar effects on crop yields

Jeffrey et al. (2011) meta- analysis of 109 independent study of the effect of biochar on crop yield reported an average increase in yield after biochar application by 13-14% in acidic to neutral soils and by 10-13% in coarse and medium-textured soils, which are like soil in Rwanda. The largest increase of 39% was seen after biochar applications at a rate of 100 t/ha. Biochar was also shown to increase the crop yield by 25% in the tropics at a medium application rate of 15 t/ha (Jeffrey et al., 2017). Farhangi-Abriz et al. (2021) meta- analysis of 96 manuscript on various legumes plants yield response to application of biochar showed that with the biochar application rate of 1-30t/ha the plant biomass increased significantly between 13-22%.

This implies that if the same or more quantity of biochar is applied to soil in Rwanda can lead to an increase in crop productivity because soil in Rwanda shares similar properties including acidic pH and sandy or coarse texture. The response of crop yield was shown to vary with biochar type related to biochar feedstock. Biochar from manure, wood, and crop residues have been considered very significant for improving soil fertility by increasing the amounts of plants available nutrients due to improved soil structure among others (Liu et al., 2013).Therefore, the use of biochar in a degraded soil has shown a positive effect on various soil properties including CEC, pH, carbon content, soil structure and bulk density which are essential to enhance the crop production. This indicate that biochar improves the crop yield over a long period of time with less soil amendment needed than other amendment used in Rwanda

8. Potential feedstock available for biochar production in Rwanda

The choice of feedstock biomass for the production of biochar depends on the local availability of materials and costs of acquisition. Available feedstock in Rwanda includes crop residues, manure, wood wastes from forestry and agriculture wastes. Natural vegetation in Rwanda is predominantly savannah with grasses, bushes, tress, and rainforests; these materials and their byproducts are potential feedstock for biochar production. Rwanda's economy is dominated by agriculture: specifically crop production, livestock production and forestry. Rwanda's livestock population include more than 10 million farm animals. The wastes generated from agro-processing, crop residues and manure from livestock are other potential biochar feedstock available in Rwanda. Municipal solid waste is another large potential source of biochar feedstock as it comprised 70 weight percent of organic waste, food and green waste (Eliasson & Carlsson , 2020).

9. Summary and Conclusion

Current agricultural management practices in Rwanda are insufficient to maintain soil with good fertility and improve crop productivity. The addition of biochar is expected to improve productivity relevant soil characteristics such as pH, CEC, carbon content, structure, bulk density, porosity and soil structure contributing to sustainable crop production in Rwanda. Compared to non-pyrolyzed organic soil amendments such as manure or crop residues, the benefits derived from biochar has long lasting impacts (>20 years) because of its stability in soil (Wang et al., 2016). The longevity of the increase in crop yield and soil properties improvement after the application of biochar indicates that there could be potential opportunities for intensifying Rwanda's agriculture production in the farming system by using biochar as a soil amendment.

10. Outlook

Overall, biochar application to soil in Rwanda can potentially have impacts on soil properties and agriculture productivity. Based on the findings in this thesis, conducting biochar field trials and research on Rwanda would be beneficial to stimulate the interest of the farmers, stakeholders, researchers and policy makers to consider adopting biochar technology to complement current effort in agriculture sector.

On farm field trials and research could start in area of western and southern province where there is most degraded soil to decisively establish the extent of biochar application effect. The on farms pyrolizers such as pyrolytic stoves and retorts kilns that can be designed used locally available materials and technical skills appear most ideal for small farm holders in Rwanda. Rwanda has substantial potential feedstock for biochar production predominantly derived from manure, municipal solid wastes, and crop residues that could feasibly be used in the production of biochar.

11.References

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