INDUSTRIAL BIOCHAR CHARACTERIZATION: PROPERTIES AND POTENTIAL APPLICATIONS

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A CAUTION TO THE READER

This HBScF thesis has been through a semi-formal process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty, or Lakehead University.

ABSTRACT

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Key words: biochar, bioeconomy, carbon sequestration, characterization, soil amendment, renewable energy.

Biochar is a carbon-rich charcoal produced from pyrolyzed biomass such as wood, agricultural waste, or animal products. Biochar is primarily used as a soil amendment, but it has promising applications in carbon sequestration, fuel cell production, medicinal uses, as a construction material, and more. The diversity in biochar production and feedstock makes it a highly variable product. Therefore, the characterization of biochar is critical before determining potential applications. This study characterizes the biochar produced by West Fraser Timber Co., which was made using wood waste from OSB production and from the surrounding area as a feedstock. A full proximate analysis was conducted. Other relevant properties were predicted based on comparisons between available literature and the production factors of the biochar. Based on the properties, both measured and predicted, it was assessed that the biochar is applicable as a soil amendment for carbon sequestration and improving crop productivity, but not applicable as a fuel source.

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1. INTRODUCTION

Biochar is the carbon-rich solid product formed by the pyrolysis of biomass. When produced from woody biomass, biochar is sometimes referred to as charcoal (Weber and Quicker 2018). Biochar is primarily used as a soil additive to improve soil fertility and increase carbon sequestration (Igalavithana et al. 2017). When used as a soil additive, biochar is beneficial to crop productivity and a powerful tool in climate change mitigation (Woolf et al. 2010).

The diversification of biochar applications has become attractive to academia and industry stakeholders due to increased political and consumer interest in sustainably sourced carbon neutral products. Many recent studies focus on improving understanding of biochar as a soil amendment, while others examine its use in other disciplines such as renewable power generation, water remediation, textiles, medicinal uses, and more (Igalavithana et al. 2017).

The production of biochar is highly variable, resulting in a heterogeneous product (Igalavithana et al. 2017). It can be produced from many biomass feedstocks, including agricultural crops and agricultural waste, aquatic plants, wood and wood waste, manures and other animal waste, and municipal waste (Aller 2016). All of these feedstocks can be converted into biochar using several thermochemical treatments (Aller 2016). Different conditions chosen for the thermochemical treatment, such as pyrolysis temperature and heating rate, can alter the chemical properties, physical properties, and yield of the biochar (Ahmade et al. 2014). It is impossible to determine the best use for all biochars because both feedstock and production method impact the resulting biochar's properties, and properties effect potential applications. Instead, it is necessary to characterize the specific biochar to determine its optimal use (Igalavithana et al. 2017).

As more applications for biochar are discovered and the mechanisms behind its benefits understood, optimizing a biochars application is becoming increasingly feasible and effective. Businesses with a steady supply of suitable biomass now have the potential to create an additional value-added product through application-specific biochar. An OSB mill owned by West Fraser Timber produces biochar as a by-product of biomass gasification. West Fraser Timber recognized the growing market potential for what was previously considered waste, and sought to uncover for what, if anything, the biochar could be used.

1.1. OBJECTIVE

The objective of this thesis is to test the properties of the biochar product produced through biomass gasification of wood waste. Internationally recognized testing standards will be used for all property testing. The suitability of the biochar as a fuel source or soil amendment will be evaluated using a combination of literature and property testing. If not suitable to either application, recommendations will be made for modifications to the production process, additives, or alternative uses.

1.2. HYPOTHESIS

Biochar produced from the wood waste of an OSB production plant will have properties that make the product most suitable for application as an agricultural soil amendment.

2. LITERATURE REVIEW

2.1. APPLICATIONS OF BIOCHAR

2.2.1. History of Biochar

Though modern interest in biochar is rooted in an interest in technologically driven solutions to environmental problems, its history is "rooted in indigenous soil practices in the Amazon known as Terra Preta de Indio (also known as Amazonia Dark Earths)" (Bezerra et al. 2019). Indigenous people in the Amazon created Terra Preta soils between 500 - 2500 years ago (Soentgen et al. 2017). This anthropogenic modification increased soil fertility and carbon storage compared to the non-modified surrounding soil (Bezerra et al. 2019).

In the 1990s, scientists became interested in the synthetic production of Terra Preta soils as a means of carbon sequestration and fertilization (Soentgen et al. 2017; Bezerra et al. 2019). The Terra Preta Nova project was launched in 2002 and acted as an alternative to slash-and-burn agriculture in the Amazon to improve the sustainability of soil management (Bezerra et al. 2019). The concept did not gain traction outside of the Amazon until it was rebranded as biochar (Bezerra et al. 2019).

2.1.2. Current Applications

Today, biochar is primarily considered a soil amendment. Depending on its properties, it can improve soil and water remediation, soil fertility, and carbon sequestration in soil (Igalavithana et al. 2017). Biochar can benefit crop productivity when applied to agricultural soils, likely due to a liming effect, improved water holding capacity, and increased nutrient availability (Jeffery et al. 2011; Hussain et al. 2017). Biochar more effectively increases crop productivity in nutrient-poor soils (Hussain et al. 2017). When added to soil, biochar also effectively sequesters carbon (Igalavithana et al. 2017; Bezerra et al. 2019). The estimated mean residency time of biochar carbon varies depending on the biochar's chemical stability and the type of soil to which it is applied (Singh et al. 2012). A long incubation study conducted by Singh et al. (2012) suggests that both plant- and manure-based biochars are likely to have mean residence times long enough to be considered permanent in emissions trading (over 100 years).

Biochar also has applications in water remediation. Depending on feedstock and production conditions, biochar can adsorb a variety of environmentally harmful inorganics (e.g., dyes, phenolics, pesticides, and polynuclear aromatics) and organics (i.e., cations and anions) (Mohan et al. 2014). In studies and applications, biochar has been successfully used to treat groundwater, drinking water, and wastewater (Mohan et al. 2014).

Biochar can also be burned as a fuel source (Abdullah and Wu 2009). Turning biomass into biochar through pyrolysis intensifies the energy content, making it more suitable to energy applications (Lee et al. 2020). In industrial electricity generation, biochar is mostly co-fired with coal (Lee et al. 2020).

2.1.3. Emerging Markets

The sustainability, low cost, and unique properties of biochar have driven the desire to expand biochar applications (Igalavithana et al. 2017). Emerging applications include "catalysis, medicinal uses, supercapacitors, gas adsorbent, fuel cell systems, and energy/gas storage" (Igalavithana et al. 2017).

Biochar is promising as a cheaper alternative to a range of commercial catalysts. For some applications, biochar catalysts are more active and selective than their conventional counterparts (Lee et al. 2017). For example, a pine wood and peanut hull mixed feedstock biochar was used as a catalyst for the hydrolysis of xylan, and it resulted in higher conversion in less time compared to a commercial activated carbon catalyst (Lee et al. 2017). Biochar also shows promise as a cheaper alternative to commercial catalysts in removing tar produced by biomass gasification and as a catalyst in biodiesel production (Lee et al. 2017).

Direct Carbon Fuel Cells (DCFC) directly convert carbon into electricity with low carbon dioxide emissions (Ali et al. 2019). They have a theoretical efficiency of 100%, but currently only a 60% practical efficiency (Ali et al. 2019). Elleuch et al. (2013) used an almond shell biochar as fuel in a DCFC and generated higher electricity output and current density than that generated by a commercially available activated carbon. Ali et al. (2019) also found walnut shell biochar and almond shell biochar to be more effective than bituminous and lignite fuels in a DCFC but less effective than sub-bituminous coal. If the practical efficiency of DCFCs is improved, biochar will be a competitive carbon source – especially biochar currently considered waste.

2.2. BIOCHAR PRODUCTION FACTORS AND PROPERTIES

Biochar is produced alongside bio-oil and syngas, such as methane and carbon dioxide, during biomass pyrolysis (Demirbas and Arin 2002). Biomass pyrolysis is the thermochemical decomposition of biomass at high temperature in the absence of oxygen (Demirbas and Arin 2002). Pyrolysis can be divided into three categories depending on residence time and temperature: Fast pyrolysis, intermediate pyrolysis, and slow pyrolysis (Ahmad et al. 2014).

Pyrolysis can be used on a wide variety of biomass feedstocks in the production of biochar. The range of feasible feedstocks allows for the use of locally abundant waste biomass, which lowers transportation costs, acquisition costs, and the final product's overall carbon intensity (Mukome et al. 2013). Feedstock properties and production conditions, such as pyrolysis temperature, heating rate, and residence time, all influence the biochar's properties to variable degrees (Zhao et al. 2013). Overall, highest treatment temperature and feedstock have the most significant influence on biochar properties (Zhao et al. 2013). As such, the influence of feedstock and highest treatment temperature on biochar properties are best covered by the literature.

2.2.1. Biochar Yield

The residence time and temperature impact the yield of the biochar, bio-oil, and syngas produced by pyrolysis (Table 1) (Ahmad et al. 2014; Domingues et al. 2017). Zhao et al. (2013) found that biochar yield is more dependent on the highest treatment temperature than the feedstock used in production. Pyrolysis processes lasting from minutes to hours (slow and intermediate pyrolysis) reaching lower temperatures yield more biochar and are typically favoured if biochar production is the primary goal (Ahmad et al. 2014; Uchimiya et al. 2011). Gasification, where the thermal decomposition occurs with carefully controlled oxygen amounts, also produces biochar, but it is typically used when syngas or bio-oil is the primary objective (Mohan et al. 2014). Most of the decrease in yield is seen in lower temperature raises (i.e. 200 to 300°C) as moisture and labile volatile matter are released, at which point the decrease in yield becomes slower and steadier (Ahmad et al. 2014; Zhao et al. 2018). This non-linear inverse relationship between pyrolysis temperature and yield is displayed in Figure 1. The effect of pyrolysis temperature on biochar yield for different feedstocks. (Zhao et al. 2018)

Table 1. Temperature, residency time, and product distribution of the pyrolysis processes. (Ahmad et al. 2014)

Process	Temperature (°C)	Residence Time	Bio-oil (%)	Biochar (%)	Syngas (%)
Fast pyrolysis	300 – 1000	Short (<2 s)	75	12	13
Intermediate pyrolysis	~500	Moderate (10 – 20 s)	50	25	25
Slow pyrolysis	100 – 1000	Long (5 – 30 min)	30	35	35
Gasification	>800	Moderate (10 – 20 s)	5	10	85

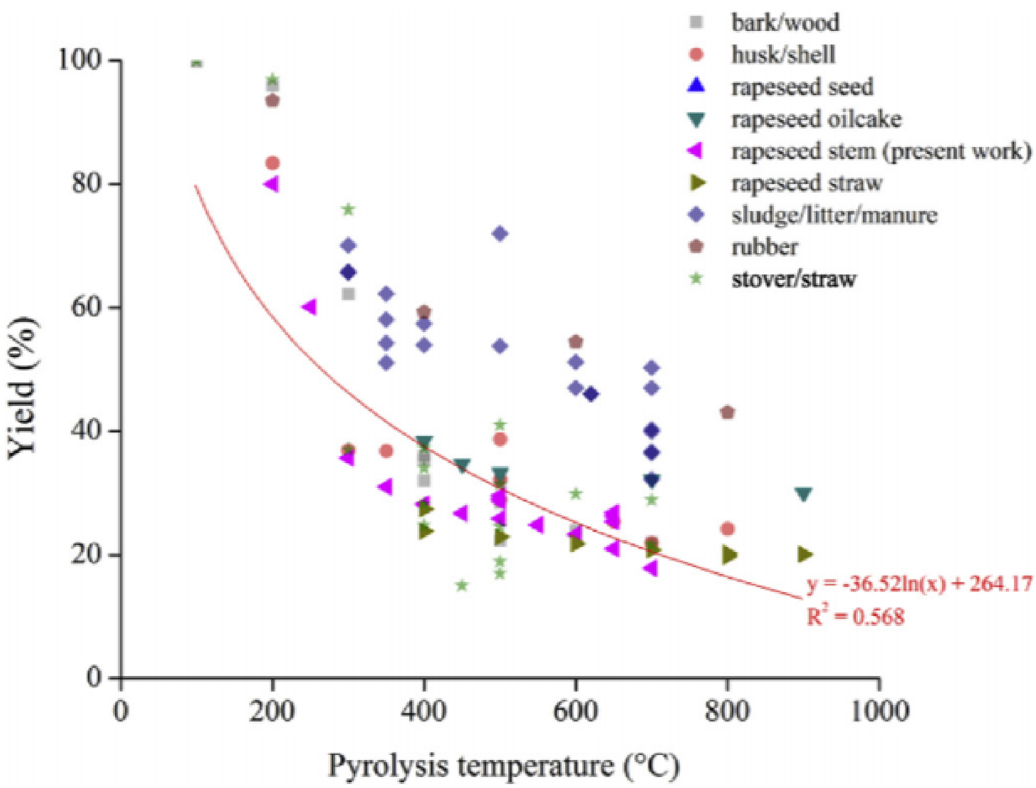

Figure 1. The effect of pyrolysis temperature on biochar yield for different feedstocks. (Zhao et al. 2018)

The feedstock used in biochar production is the most influential factor in defining the final product's properties (Aller 2016; Domingues et al. 2017). Feedstock biomass with high amounts of inorganic compounds, such as manures and municipal waste, typically result in higher yields (Domingues et al. 2017). However, this increased yield is primarily in ash content (Domingues et al. 2017). Feedstocks high in lignin, versus cellulose or hemicellulose, are also expected to result in a higher biochar yield (Uchimiya et al. 2011).

2.2.2. Ash Content

Ash content is more dependent on feedstock than it is on pyrolysis temperature (Mukome et al. 2013; Zhao et al. 2013). Ash content in the resulting biochar is positively correlated to the amount of inorganic compounds and nutrients in the feedstock (Domingues et al. 2017). The presence of larger quantities of ash may hinder the formation of aromatic structures during pyrolysis, meaning higher ash content is negatively correlated to aromatic carbons and fixed carbon content (Domingues et al. 2017). Ash content of the biochar is dependent on the ash content of the feedstock: High ash content feedstock (ex. grass) results in biochar with higher ash content than feedstocks with lower ash content (ex. wood) (Uchimiya et al. 2011).

Though less critical, ash content is also affected by pyrolysis temperature. Ash contents are generally found to increase with an increase in pyrolysis temperature across all feedstock types (Domingues et al. 2017; Uchimiya et al. 2011).

The composition of the ash is also relevant to some applications. Ash composition is primarily determined by feedstock. Biochars produced from agricultural residues tend to have ashes with higher alkali and alkaline earth metal content than biochars produced from woody biomass (Liu et al. 2015).

2.2.3. pH

The pH of biochar depends on both feedstock and treatment temperature (Mukome et al. 2013; Zhao et al. 2013; Ahmad et al. 2014); however, it is mainly influenced by treatment temperature (Zhao et al. 2013). In a statistical scan of the literature, Zhao et al. (2018) found pyrolysis temperature to significantly positively correlate with the resulting biochar's pH values. In their testing of biochars produced with different temperatures using rapeseed stem feedstock, Zhao et al. (2018) observed a general increase of pH with pyrolysis temperature, with a slight dip between 450 and 550° Celsius. The relationship between pyrolysis temperature and pH likely has two causes: The increase of alkaline ash with temperature and the decrease of acidic functional groups (phenolic and carboxylic groups) with temperature (Zhao et al. 2018).

Though less significant, the feedstock does influence biochar pH. In a study testing differences between biochar's produced from 12 different feedstocks, Mukome et al. (2013) found that non-wood (i.e., manure, grass, algae) derived biochars tend to have higher pH than their woody counterparts when all other production factors are constant. Within wood-based feedstocks, softwoods are more likely to produce more acidic biochar than hardwoods (Mukome et al. 2013).

2.2.4. Surface Area

Biochar surface area is more influenced by pyrolysis treatment temperature than by feedstock selection (Zhao et al. 2013; Mukome et al. 2013; Zhao et al. 2018). Biochar surface area tends to increase with an increase in pyrolysis temperature (Uchimiya et al. 2011; Ahmad et al. 2014; Brewer et al. 2009; Sun et al. 2014; Zhao et al. 2018). A maximum surface area is typically produced with treatment temperatures between 500 and 900° C depending on feedstock and other pyrolysis variables (Uchimiya et al. 2011). For example, the surface area is also significantly influenced by the heating rate and the pyrolysis residence time - a production factor often ignored by studies (Zhao et al. 2018).

Feedstock also influences the biochar surface area, but to a lesser extent. Animal waste and solid waste feedstocks produce biochars with lower surface areas than crop residue and woody biomass (Ahmad et al. 2014). Crop residue and grass chars typically have lower surface area than biochar's from wood feedstocks (Uchimiya et al. 2011).

2.2.5. Pore Size

Pore volume is influenced by both feedstock and production temperature (Zhao et al. 2013). Feedstock has a greater influence on pore size because the biochar retains characteristics of the physical structure through the pyrolysis (Trigo et al. 2016). Hyvaluoma et al. (2018) tested biochar produced from willow wood at pyrolysis temperatures between 300 and 500° C and reported that it was the "vascular cell structure" of the wood that determined the micrometre-range porosity.

At higher temperatures, pore volume is most influenced by pyrolysis temperature. Pyrolysis temperature has a negative relationship with average pore diameter but a positive relationship with total pore volume (Suliman et al. 2016; Trigo et al. 2016; Zhao et al. 2018). Suliman et al. (2016) found that for biochar made of Douglas fir wood, Douglas fir bark, or hybrid poplar wood, with maximum pyrolysis temperatures between 623 and 873° C, micropore volume increased with pyrolysis temperature. Beyond a certain temperature (ex. 800° C for macadamia nutshell biochar), pore volume begins to decrease as pores fuse (Zhao et al. 2018).

2.2.6. Elemental Composition

Biochar is primarily composed of carbon. Carbon content is influenced by treatment temperature and feedstock (Singh et al. 2010) but it is more influenced by feedstock (Zhao et al. 2013). Wood feedstocks produce biochars with the highest carbon content, followed by leaf biomass and crop waste, while manure feedstocks produce the lowest carbon content biochar (Singh et al. 2010; Sun et al. 2014; Gul et al. 2015). The carbon content is also influenced by treatment temperature, though the effect it has is dependent on the feedstock. For plant-based and woody feedstocks, an increase in treatment temperature increases the biochars carbon content (Singh et al. 2010). For animal waste feedstocks, an increase in treatment temperature decreases the biochars carbon content (Singh et al. 2010).

Plant based biochars, both woody and non-woody, tend to have low nitrogen, phosphorous, potassium, sulfur, calcium, magnesium, aluminum, sodium, and copper contents when compared to manure-based biochars (Singh et al. 2010). Phosphorous, potassium, and calcium all increase with treatment temperature increases (Gul et al. 2015). Hydrogen and oxygen content decrease with increasing treatment temperatures (Sun et al. 2014).

2.3. IMPORTANCE OF BIOCHAR CHARACTERIZATION

It is vital to characterize biochar before application; however, there are no internationally recognized standards for general biochar characterization. All existing biochar characterization frameworks, such as the one produced by the International Biochar Institute (IBI) (2015), are focussed on use as soil or agricultural amendment. There are no recognized guidelines for use in other disciplines (Igalavithana et al. 2017).

This makes it difficult to determine which properties to test when looking to optimize the use of a specific biochar. Instead, it is best to consider possible uses and analyze how various testable properties influence the biochar's performance in that application. For the sake of this thesis, properties will be considered through the perspective of using the biochar as a soil amendment and as a fuel source.

2.3.1. Important Characteristics for Soil Applications

Biochar can be used as a soil amendment to sequester carbon, enhance soil fertility, and improve nutrient and water-use efficiency (Singh et al. 2010). Biochar characteristics, as influenced by the feedstock and production conditions, favour different types of soils and different goals for the application (Singh et al. 2010). There are three soil applications of interest currently in the U.S.A.: as a carbon sequestration technique, to improve crop productivity, and on land where carbon amendment applications will improve soil carbon under the Soil Carbon Amendment (808) soil conservation standard.

2.3.1.1. As a Carbon Sequestration Technology

As public attention to climate change increases, so to does the pressure on businesses and policy makers to intervene. As countries and companies alike strive for carbon neutrality, the market for carbon sequestration technologies grows. Biochar can be a negative emission technology if the amount of carbon sequestered in soil is greater than that released from production and transportation (IPCC 2019). In late 2020, a company called Pacific Biochar was the first U.S.A. based company to receive carbon credits for biochar through Carbonfuture (Norris 2020). Pacific Biochar produces biochar from sawmill and logging residues (Norris 2020).

A biochar must be able to resist degradation to effectively sequester carbon in soil long enough to be considered permanent in carbon trading (Zhao et al. 2013). The ability to resist degradation is often referred to as recalcitrance. The R_{50} recalcitrance index was developed by Harvey et al. (2012) to quantify this critical property. The R_{50} is based on the temperature value corresponding to 50% oxidation/volatilization of the biochar as obtained through thermogravimetric analysis (Harvey et al. 2012). This value is then divided by the temperature value corresponding to 50% oxidation/volatilization of graphite to achieve a value from 0 to 1, with 1 being the most recalcitrant material (Harvey et al. 2012). The recalcitrance of biochar tends to increase with treatment temperature (Singh et al. 2010; Harvey et al. 2012).

Biochar recalcitrance can also be estimated using a proximate analysis. The volatile matter to fixed carbon ratio can be used to estimate the labile and recalcitrant biochar fractions (Archontoulis et al. 2016; Aller et al. 2017). A higher percentage of volatile matter means that the biochar likely has a higher labile fraction, while a higher percentage of fixed carbon means that the biochar likely has a higher recalcitrant fraction (Aller et al. 2017). However, further research is needed to determine whether the labile fraction discovered thermally (volatile matter) is indicative of the biologically labile fraction (Aller et al. 2017).

2.3.1.2. To Improve Crop Productivity

Most studies on the effect of biochar soil amendments on crop productivity are based on short-term experiments ranging from 1 to 2 years (Hussain et al. 2017). For a biochar soil amendment to be safe and worthwhile in terms of crop productivity, the properties of both the soil and the biochar must be known. Biochar created from all feedstocks can increase yield and biomass on treated fields; however, if the wrong type of biochar is applied in certain situations, it can also decrease crop productivity (Hussain et al. 2017).

Jeffrey et al. (2011) conducted a meta-analysis of available studies and concluded that biochar application positively impacts crop productivity on average. Jeffrey et al. (2011) suggests that the two main mechanisms for crop productivity improvement are a liming effect and improved water holding capacity in coarse and medium textured soils. The liming ability of biochars is related to the pH of the biochar and negatively charged functional groups on the biochars surface (Gul et al. 2015). Water holding capacity is influenced by the physical structure of biochars, including the surface area, pore volume, and average pore size (Hyvaluoma et al. 2018; Zhao et al. 2013).

The C:N ratio of biochar is a predictor of nitrogen mineralization and immobilization (Singh et al. 2010). This can be detrimental to crop productivity if a high C:N ratio biochar is intended for use in nitrogen deficient soils (Asai et al. 2009; Hussain et al. 2017). This can be counteracted with nitrogen fertilizers (Asai et al. 2009).

The chemical composition of the biochar must also be considered. If a biochar is high in nutrients such as phosphorus, potassium, calcium, or magnesium, it can act as a mineral nutrient supplement comparable to commercial fertilizers (Luo et al. 2014).

2.3.1.3. For the Soil Carbon Amendment (808) Conservation Standard

The Soil Carbon Amendment (808) is a USDA interim conservation practice standard which promotes the use of plant or animal derived soil amendments to increase soil carbon and improve soil health (USDA, NRCS 2019). For biochar to be used under this standard, an analysis must be done of its carbon, nitrogen, potassium, phosphorous, and pH or it must have the International Biochar Institute Seal (USDA, NRCS 2019). This requirement means that for a biochar to be applicable for application under Soil Carbon Amendment (808), production factors such as feedstock and highest treatment temperature must be constant and known.

The application of biochars with C:N ratios greater than 25:1, risks immobilizing other nutrients, but this can be mitigated by mixing nutrient-rich compost with the biochar prior to application (USDA, NRCS 2019). If the biochar is composed of more than 60% carbon, it is likely to reduce phosphorus losses (USDA, NRCS 2019). Farmers with eligible land in 20 states can receive financial assistance through NRCS to apply biochar or a mixture of compost and biochar to their fields.

2.3.2. Important Characteristics for Fuel Application

The ash content and ash composition have the most influence on the feasibility of using a biochar as a fuel source. The combustion of biochars with high ash content leads to ash accumulation which can be expensive and inefficient to remove (Liu et al. 2015). Additionally, high ash content lowers the calorific value of the biochar (Tumutegyereize et al. 2016). If the biochars ash is high in alkali and alkaline earth metals content, then it can also result in slagging and fouling of the boiler (Liu et al. 2015).

Moisture is another critical property for potential fuel sources. Low moisture content is desired in thermochemical processes (Abdullah et al. 2010). When a fuel source has a high moisture content, a percentage of the fuel input is used to evaporate the moisture (Karthikeyan et al. 2009). Most biochar production processes result in a biochar with low moisture content (Abdullah and Wu 2009). There is no literature related to drying high-moisture biochar or charcoal. Drying coal, however, is the subject of literature due to the benefits of drying low-rank coal prior to use (Karthikeyan et al. 2009), and some of the techniques may be transferable if needed.

The atomic H/C and O/C ratio of biochars influence their performance as a fuel source (Abdullah and Wu 2009). Generally, fuel sources with low H/C and O/C ratios perform more efficiently due to reduced energy loss, smoke, and water vapor (Abdullah and Wu 2009). Furthermore, low H/C and O/C ratios are correlated with more carbon-carbon bonds, which contain more energy than carbon-hydrogen or carbon-oxygen bonds (Abdullah and Wu 2009). Fuels with low H/C and O/C ratios tend to have higher mass energy densities (Abdullah and Wu 2009).

The fuel ratio of biochar is an indicator of combustion efficiency and pollutant emissions (Liu and Han 2015). The fuel ratio is a ratio between fixed carbon and volatile matter (Liu and Han 2015). A biochar with a high fuel ratio is likely to have higher combustion efficiencies and lower pollutant emissions that a biochar with a low fuel ratio (Liu and Han 2015).

The grindability of a fuel source is relevant to performance because it influences volume energy density. One of the primary drawbacks of biomass as a fuel source is poor grindability, which conversion to biochar improves (Abdullah and Wu 2009).

Highly grindable materials can be ground to reduce size and combustion efficiency thus increasing bulk density and volumetric energy density (Abdullah and Wu 2009).

3. MATERIALS AND METHODS

3.1. BIOCHAR PRODUCTION

Biochar produced by West Fraser Timber Co. Ltd. in Alabama, USA, was used. West Fraser in Alabama and South Carolina operates three train rotary kiln gasifiers, manufactured by Callidus,. Biochar is a by-product of the process, with steam being the primary product. The kilns have been modified to include a submerged ash conveyor system for safety reasons, which water-logs the biochar immediately after production (Figure 2).

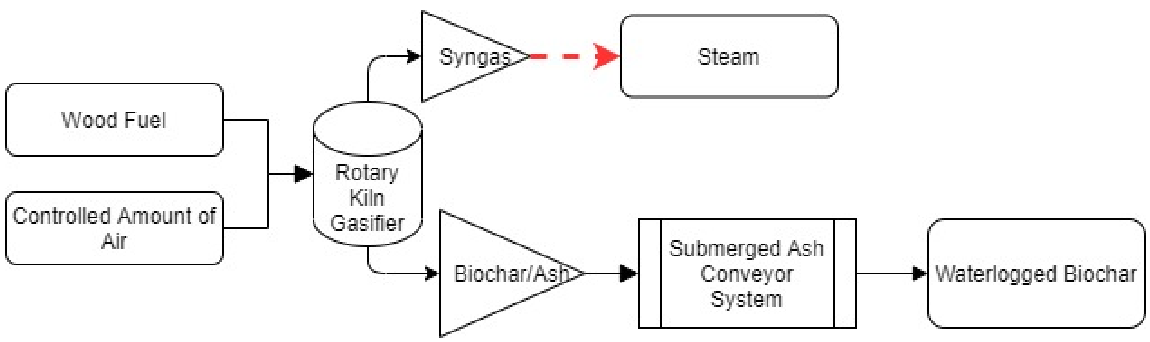

Figure 2. Simplified flow diagram of the Calidus rotary kiln gasifier system. The red dotted arrow represents parts of the process irrelevant to the biochar production.

In both locations, the kilns are attached to OSB mills and utilize a combination of wood waste from the mill and biomass from the surrounding area. The feedstock is approximately 50% wood and bark from "Southern Yellow Pine" (SYP) recovered from the mills debarkers, and 50% purchased biomass, mostly in the form of wood chips of undetermined species. SYP is a group of four species growing in Southern USA, including loblolly pine (*Pinus taeda* L.), slash pine (*Pinus elliottii* Engelm.), shortleaf pine (*Pinus echinata* Mill.), and longleaf pine (*Pinus palustris* Mill.).

The feedstock is fed into the kiln gasifier and combined with a controlled amount of oxygen to allow the gasification process to occur. Difficulty controlling oxygen intake inherent to the rotary kiln gasifier design and a lack of oxygen sensors capable of withstanding the internal heat result in uncertainty regarding oxygen presence in the reaction. The gasifiers operate at upwards of 650° C and have a wood fuel residence time of approximately 60 minutes (Fosgitt 2010). The resulting biochar is a waste product and is dropped into a water conveyor system for safety purposes.

One kilogram of the waste biochar was provided. The biochar was ground using a mortar and pestle prior to all tests (Figure 3). Half of the ground biochar was dried in a kiln while the other half was stored as is in plastic containers.

Figure 3. The biochar after being ground with the mortar and pestle.

3.2. BIOCHAR CHARACTERIZATION

3.2.1. Proximate Analysis

The proximate analysis was conducted by the Lakehead University Wood Science Testing Facility using a Loss-On-Ignition (LOI) method to determine the ash, moisture, volatile matter (VM), and fixed carbon (FC) contents of the biochar. A Leco TGA-601 Thermogravimetric Analyzer (TGA) was used (Figure 4).

Figure 4. The Leco TGA-601 Thermogravimetric Analyzer conducting a proximate analysis.

Six empty crucibles were placed into the TGAs carousel. Half of the crucibles were loaded with biochar that had been ground and dried, while the other half were loaded with biochar that had only been ground. All six samples were around 1 gram, as required by the machine. The dried samples were used to measure VM, FC, and ash content. The ground but not dried samples were used to measure total moisture.

The LOI method used reaches a maximum temperature of 900° C to separate VM and FC. Once the TGA was complete, the associated software recorded the initial weight, moisture, VM, ash, FC, VM on a dry basis, ash on a dry basis, FC on a dry basis, and corrected volatile matter. All data was transferred to excel for analysis and can be found in Appendix I.

4. RESULTS

The results of the proximate analysis for the three dried samples are shown in Table 2. The mean VM of the three samples was 13.74% (SD = 0.67%). The mean ash content of the three samples was 11.32% (SD = 0.32%). The mean FC of the three samples was 74.94% (SD = 0.99%).

Table 2. Proximate analysis results. Percent weight on dry basis.

Sample #	VM	Ash	Fixed Carbon
1	12.81	10.88	76.31
2	14.37	11.62	74.01
3	14.04	11.47	74.49

Based on the TGA results for the three wet samples, the mean moisture content of the biochar was 60.02% (SD = 3.05%).

5. DISCUSSION

5.1. PRODUCTION FACTORS INFLUENCE ON PROPERTIES

The biochar characterized in this study was produced from a mixture of woody biomass, at least 50% of which comes from softwood species, at temperatures exceeding 650° Celsius. Table 3 was constructed to provide estimates of the biochars properties based on the known production conditions and the literature.

Table 3. Likely ranges of the biochars properties based on the production factors and literature.

Property	Likely Range	Justification	Source
Ash Content (%)	Low	Wood feedstocks produce biochars with low ash content regardless of production temperature.	Singh et al. 2010; Uchimiya et al. 2011; Domingues et al. 2017
pH	Moderately high (Alkaline)	Biochar pH is mainly influenced by treatment temperature - positive correlation between treatment temperature and pH. To a lesser extent, the softwood feedstock likely lowers the pH.	Singh et al. 2010; Mukome et al. 2013; Zhao et al. 2013; Zhao et al. 2018
Surface Area	High	Surface area is positively corelated with production temperature. Maximum usually seen at temperatures between 500° C and 900° C. Wood feedstocks produce higher surface area biochars.	Uchimiya et al. 2011; Ahmad et al. 2014; Zhao et al. 2018
Electrical Conductivity	Low	Wood feedstocks produce biochars with low EC values regardless of production temperature.	Singh et al. 2010

Table 3. (Continued)

Property	Likely Range	Justification	Source
C:N Ratio	High	Biochars made from wood feedstocks generally have high total C content and low total N content. C content further increases with temperature.	Brewer et al. 2009; Singh et al. 2010; Zhao et al. 2013; Ahmad et al. 2014; Gul et al. 2015
Total N, P, K, S, Ca, Mg, Al, Na, and Cu contents	Low	Primarily dependent on feedstock. Low for biochars made from woody feedstocks.	Singh et al. 2010; Gul et al. 2015
H and O contents	Low	H and O contents decrease with increasing treatment temperature.	Sun et al. 2014
CEC	Low	Wood feedstocks produce low CEC biochars. CEC is also negatively corelated with production temperature.	Singh et al. 2010; Zhao et al. 2013; Gul et al. 2015
Moisture Content	Very high	Dropped into water conveyor post-production leading to a waterlogged biochar.	N/a
Recalcitrance	High	High production temperatures produce biochars with high recalcitrance.	Singh et al. 2010; Zhao et al. 2013; Rittl et al. 2018

Predicting properties of the biochar is complicated by the unknown and variable nature of the feedstock. The feedstock is wood waste and bark from SYP combined with other woody biomass of unidentified species. Of the predicted properties above the ash content, pore size, elemental composition, EC, and CEC are the most strongly influenced by feedstock (Brewer et al. 2009; Singh et al. 2010; Zhao et al. 2013) and are therefore the most likely to vary in the final product. The variability in production temperature and oxygen content further increases the uncertainty of the biochar.

For the remainder of the thesis, the predicted ranges and results will be considered accurate and consistent for the biochar. Variability will only be considered if it would hamper the certification or application of the biochar.

5.2. SUITABILITY OF THE BIOCHAR AS A SOIL AMENDMENT

5.2.1. As a Carbon Sequestration Technology

The results of the proximate analysis suggest that the biochar is suitable for application to sequester carbon. The mean fixed carbon content was nearly 75%, which suggests that most of the carbon in the biochar is recalcitrant (Archontoulis et al. 2016). Zhao et al. (2013) found that high temperature pyrolysis or gasification create biochars with high recalcitrance, noting that the main disadvantage is that high temperatures result in low yields. Thus, when produced at high temperatures, biochar does not store a lot of the carbon from the biomass, but that which it does will likely remain in the soil for a long time. This is favourable for the biochar tested in this study because it is a by-product and therefore the biochar yield of the production is irrelevant.

Some studies show that biochar soil amendments increase soil GHG emissions in the short term. Rittl et al. (2018) suggest that using biochars made at high temperatures with high C:N ratios mitigates the problem of initial emissions. Since the biochar tested in this thesis was made at high temperatures and likely has a high C:N ratio (C content having been tested, N content predicted based on literature) GHG emissions after application are not likely to be a problem.

It is unlikely that the variability in the production factors will influence the biochars recalcitrance since it is mostly influenced by production temperature (Rittl et al.

2018). However, it may not be applicable for carbon sequestration with current carbon offset companies. Carbonfuture is a carbon offset company that utilizes biochar, but they require biochar produced in certified plants with trackable supply chains. Puro.earth requires a Lifecycle Assessment or Environmental Product declaration that verifies the product as absorbed more carbon than it has emitted. There are few North American companies that produce biochar for carbon offset companies, and it seems unlikely that the production of this biochar would meet the stringent requirements of the industry as it is now. However, as carbon credits become more common, there may be a market for this biochar in the carbon sequestration industry.

Overall, the literature and the proximate analysis results both suggest that the biochar properties lend themselves to carbon sequestration because of high recalcitrance and low GHG emissions after application. The only issue is certification for use.

5.2.2. To Improve Crop Productivity

Biochar has two main mechanisms that improve crop productivity: A liming effect and increased water holding capacity (Jeffrey et al. 2010).

The liming effect is primarily influenced by the pH of biochar. Due to the high production temperature, the pH of the biochar is likely high enough to induce the liming effect. However, this is only likely to improve crop productivity on acidic soils (Ahmad et al. 2014). If applied to a soil with a sufficient amount of organic matter, increasing the soil pH helps increase the soils CEC regardless of the biochars CEC (Gul et al. 2015). For coarse textured soils with low organic matter, co-amending the biochar with compost would likely boost CEC, soil organic matter, and soil aggregation (Gul et al. 2015).

The soils water holding capacity is influenced by different physical properties of the biochar, including the surface area, pore volume, and average pore size (Zhao et al. 2013; Hyvaluoma et al. 2018). Surface area and pore volume both increase with production temperature which is related to the biochars water holding capacity (Zhao et al. 2013); therefore, it is likely that the biochar would increase water holding capacity if applied as a soil amendment.

Before application, the elemental composition of the biochar should be determined. Since the biochar was produced from a woody feedstock, it is likely low in N P, K, S, Ca, Mg, Al, Na, and Cu (Singh et al. 2010; Gul et al. 2015). When combined with a high carbon content, this can lead to nitrogen mineralization and immobilization (Singh et al. 2010). If the biochar is to be applied to a nitrogen deficient soil, nitrogen fertilizer should also be used. It is unlikely that the biochar would be a significant source of other nutrients to the crops, but it may improve nutrient retention for the same reasons it would improve water holding capacity (Gul et al. 2015).

Since most studies on the influence of biochar as a soil amendment are short-term, the long-term influence of biochar on soil properties is poorly understood. However, the existence of Terra Preta soils in the amazon to this day suggest that the impact of soil amendment is long-lasting and may develop over time. The improvement and stabilization of pH and CEC over time do seem to be benefits of biochar application (Singh et al. 2010; Gul et al. 2015).

It is unlikely that the variability of the production process and feedstock would make the biochar properties variable enough to impact its performance as a soil amendment. It would complicate certifying the biochar, but that is not necessary for sale or application in the United States.

5.2.3. For the Soil Carbon Amendment (808) Conservation Standard

As determined by the proximate analysis and predicted based on the literature, the biochar has a high carbon content which is needed for this standard. The predicted high surface area and low oxygen content and the measured high carbon content make the biochar well suited to increase soil aggregation (Gul et al. 2015), which is one of the purposes of the standard. Additionally, as shown in the crop productivity section above, the biochar does seem promising as a general tool to improve soil health and increase crop productivity, particularly when mixed with compost as suggested in the standard.

Unfortunately, it is unlikely that the biochar would be applicable to the standard due to the variability of the production method and the feedstock. It would not be able to get certified by the IBI (IBI 2015). The Soil Carbon Amendment (808) standard specifies that carbon, nitrogen, phosphorous, potassium, and pH need to be reported, but it doesn't specify how much variability in the results is permitted or how often the analysis needs to be conducted.

5.3. SUITABILITY OF THE BIOCHAR AS A FUEL SOURCE

The proximate analysis revealed that the ash content of the biochar is high for a fuel source, with a mean of 11.32%. It is likely so high because of the high production temperature. High ash content may also be attributable to complete combustion of some of the biomass due to the difficulty controlling oxygen inherent to the rotary kiln gasifier design. At 11.32% ash content, the biochar could still be used as a fuel, but the boiler would have to be cleaned regularly. High ash content also correlates with a lower calorific value (Tumutegyereize et al. 2016).

The composition of the ash content could also be problematic. If it has a large component of alkali or alkaline earth metals, slagging or fouling would be a major concern with the total ash content so high (Liu et al. 2015). The ash is likely alkaline due to the high production temperature (Zhao et al. 2018).

The high moisture content of the biochar is the largest barrier to use as a fuel source (Karthikeyan et al. 2009; Abdullah et al. 2010). The high moisture content was expected because the biochar is intentionally dropped into a water conveyor during the production process. The measured mean moisture content is 60.32% on a wet basis, which converts to over 150% on a dry basis. Karthikeyan et al. (2009) reviewed industrial scale coal drying technologies, the best of which could only handle coal up to 80% moisture content on a dry basis. It does not seem feasible to dry this biochar prior to use as a fuel source.

6. CONCLUSION

The biochar industry is still relatively new. The shortage of standards, certifications, regulations, and standardized testing procedures makes it difficult to optimize the utilization of a biochar that is a by-product and was not made for a specific application. However, using a mixture of literature and characterization, it is possible to determine the best use out of current common applications.

The biochar produced by West Fraser Timber Co. is not a feasible fuel source due to its high moisture content and ash content. Although both issues could be mitigated with further processing, it is unlikely that doing so would be economically viable.

Conversely, the biochar is well suited to application as a soil amendment. The production factors and the proximate analysis both suggest that the biochar is carbon rich and highly recalcitrant, which indicates a high carbon sequestration potential. It is also promising as a tool to improve crop productivity, particularly on acidic soils with sufficient organic matter. Additionally, since the USDA is showing increased interest in the potential of biochar for agricultural soil health, there is a good chance that the market for biochar as a soil amendment near the mills in Alabama and South Carolina will grow in the near future.

LITERATURE CITED

Abdullah, H. and H. Wu. 2009. Biochar as a fuel: 1. Properties and gridability of biochars produced from pyrolysis of mallee wood under slow-heating conditions. Energy & Fuels. 23. 4174 – 4181.

Abdullah, H., K.A. Mediaswanti, and H. Wu. 2010. Biochar as a fuel: 2. Significant differences in fuel quality and ash properties of biochars from various biomass components of mallee trees. Energy & fuels. 24: 1972 – 1979.

Ahmad, M., A. U. Rajapaksha, J.E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S. S. Lee, and Y. S. Ok. 2014. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere. 99: 19 – 33.

Ali, A., R. Raza, M.I. Shakir, A. Iftikhar, F. Alvi, M.K. Ullah, A. Hamid, and J. Kim. 2019. Promising electrochemical study of titanate based anodes in direct carbon fuel cell using walnut and almond shells biochar fuel. Journal of Power Sources. 434: 126679.

Aller, D., S. Bakshi, and D.A. Laird. 2017. Modified method for proximate analysis of biochars. Journal of Analytical and Applied Pyrolysis. 124: 335 – 342.

Aller, M. F. 2016. Biochar properties: Transport, fate, and impact. Critical Reviews in Environmental Science and Technology. 46(14 – 15): 1183 – 1296.

Archontoulis, S.V., I. Huber, F.E. Miguez, P.J. Thorburn, N. Rogovska, and D.A. Laird. 2016. A model for mechanistic and system assessments of biochar effects on soil and crops and trade-offs. GCB Bioenergy. 8: 1028 – 1045.

Asai, H., B.K. Samson, H.M. Stephan, K. Songyikhangsuthor, K. Homma, Y. Kiyono, Y. Inoue, T. Shiraiwa, and T. Horie. 2009. Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Research. 111: 81 – 84.

Bezerra, J., E. Turnhout, I.M. Vasquez, T.F. Rittl, B. Arts, and T.W. Kuyper. 2019. The promises of the Amazonian soil: shifts in discourses of Terra Preta and biochar. Journal of Environmental Policy and Planning. 21(5): 623 – 635.

Demirbas, A., and G. Arin. 2002. An Overview of Biomass Pyrolysis. Energy Sources. 24: 471 – 482.

Domingues, R.R., P.F. Trugilho, C.A. Silva, I.C.N.A. de Melo, L.C.A. Melo, Z.M. Magriotis, and M.A. Sanchez-Monedero. 2017. Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. PLOS ONE. 1 – 19.

Elleuch, A., A. Boussetta, J. Yu, K. Halouani, and Y. Li. 2013. Experimental investiagion of direct carbon fuel cell fueled by almond shell biochar: Part I. Physicochemical characterization of the biochar fuel and cell performance examination. International Journal of Hydrogen Energy. 38: 16590 – 16604.

Fosgitt, R.L. 2010. Gasification using rotary kiln technology. Report, Wilcox Professional Services, Michigan. 20pp.

Gul, S., J.K. Whalen, B.W. Thomas, V. Sachdeva, and H. Deng. 2015. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. Agriculture, Ecosystems and Environment. 206. 46 – 59.

Harvey, O.R., L. Kuo, A.R. Zimmerman, P. Louchouarn, J.E. Amonette, and B.E. Herbert. 2012. An Index-Based Approach to Assessing Recalcitrance and Soil Carbon Sequestration Potential of Engineered Black Carbons (Biochars). Environ. Sci. Technol. 46: 1415 – 1421.

Hussain, M., M. Farooq, A. Nawaz, A.M. Al-Sadi, Z.M. Solaiman, S.S. Alghamdi, U. Ammara, Y.S. Ok, and K.H.M. Siddique. 2017. Biochar for crop production: potential benefits and risks. J. Soils Sediments. 17: 685 – 716.

Hyvaluoma, J., M. Hannula, K. Arstila, H. Wang, S. Kulju, and K. Rasa. 2018. Effects of pyrolysis temperature on the hydrologically relevant porosity of willow biochar. Journal of Analytical and Applied Pyrolysis. 134: 446 – 453.

IBI. 2015. Standardized product definition and product testing guideliines for biochar that is used in soil. https://www.biochar-international.org/wp-content/uploads/2018/04/IBI_Biochar_Standards_V2.1_Final.pdf. Oct. 22, 2020.

Igalavithana, A. D., S. Mandal, N. K. Niazi, M. Vithanage, S. J. Parikh, F. N. D. Mukome, M. Rizwan, P. Oleszczuk, M. Al-Wabel, N. Bolan, D. C. W. Tsang, K. Kim, and Y. S. Ok. 2017. Advances and future directions of biochar characterization methods and applications. Critical Reviews in Environmental Science and Technology.

IPCC. 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Jeffery, S., F.G.A. Verheijen, M. van der Velde, and A.C. Bastos. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture, Ecosystems & Environment. 144(1): 175 – 187.

Karthikeyan, M., W. Zhonghua, and A.S. Mujumdar. 2009. Low-rank coal drying technologies – current status and new developments. Drying Technology. 27: 403 – 415.

Lee, J., K. Kim, and E.E. Kwon. 2017. Biochar as a catalyst. Renewable and Sustainable Energy Reviews. 77: 70 – 79.

Lee, M., Y. Lin, P. Chiueh, and W. Den. 2020. Environmental and energy assessment of biomass residues to biochar as fuel: A brief review with recommendations for future bioenergy systems. Journal of Clearner Production. 251: 119714.

Liu, Z. S.K. Hoekman, R. Balasuramanian, and F. Zhang. 2015. Improvement of fuel qualities of solid fuel biochars by washing treatment. Fuel Processing Technology. 134: 130 – 135.

Liu, Z., and G. Han. 2015. Production of solid fuel biochar from waste biomass by low temperature pyrolysis. Fuel. 158: 159 – 165.

Luo, Y., J. Y. Jiao, X. Zhao, G. Li, L. Zhao, and H. Meng. 2014. Improvement to maize growth caused by biochars derived from six feedstocks prepared at three different temperatures. Journal of Integrative Agriculture. 13 (3): 533 – 540.

Mohan, D., A. Sarswat, Y. S. Ok, and C. U. Pittman Jr. 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – A critical review. Bioresource Technology. 16: 191 – 202.

Mukome, F.N.D., X. Zhang, L.C.R. Silva, J. Six, and S.J. Parikh. 2013. Use of chemical and physical characteristics to investigate trends in biochar feedstocks. Journal of Agricultural and Food Chemistry. 61: 2196 – 2204.

Norris, B. 2020. Pacific Biochar Lands First U.S. biochar carbon sink credits. https://pacificbiochar.com/first-biochar-carbon-credits/#:~:text=Sonoma%20County%2C%20CA%20%E2%80%93%20On%20November,needed%20to%20address%20climate%20change. Feb. 11, 2021.

Rittl, T.F., K. Butterbach-Bahl, C.M. Basile, L.A. Pereira, V. Alms, M. Dannenmann, E.G. Couto, and C.E.P. Cerri. 2018. Greenhouse gas emissions from soil amended with agricultural residue biochars: Effects of feedstock type, production temperature and soil moisture. Biomass and Bioenergy. 117: 1 – 9.

Singh, B., B.P. Singh, and A.L. Cowie. 2010. Characterisation and evaluation of biochars for their application as a soil amendment. Australian Journal of Soil Research. 48: 516 – 525.

Singh, B.P., A.L. Cowie, and R.J. Smernik. 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. Environ. Sci. Technol. 46: 11770 – 11778.

Soentgen, J., K. Hilbert, C. Groote-Bidlingmaier, G. Herzog-Schroder, E.E. Pabst, and S. Timpf. 2017. Terra preta de indio: Commodification and mythification of the Amazonian Dark Earths. GAIA. 26(2): 136 – 143.

Suliman, W., J.B. Harsh, N.I. Abu-Lail, A. Fortuna, I. Dallmeyer, and M. Garcia-Perez. 2016. Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. Biomass and Bioenergy. 84: 37 – 48.

Sun, Y., B. Gao, Y. Yao, J. Fang, M. Zhang, Y. Zhou, H. Chen, and L. Yang. 2014. Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. Chemical Engineering Journal. 240: 574 – 578.

Trigo, C., L. Cox, and K. Spokas. 2016. Influence of pyrolysis temperature and hardwood species on resulting biochar properties and their effect on azimsulfuron sorption as compared to other sorbents. Science of the Total Environment. 566 - 567: 1454 – 1464.

Tumutegyereize, P., R. Mugenyi, C. Ketlogetse, and J. Gandure. 2016. A comparative performance analysis of carbonized briquettes and charcoal fuels in Kampala-urban, Uganda. Energy for Sustainable Development. 31: 91 – 96.

Uchimiya, M., L.H. Wartelle, K.T. Klasson, C.A. Fortier, and I.M. Lima. 2011. Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. Journal of Agricultural and Food Chemistry. 59: 2501 – 2510.

USDA, NRCS. 2019. Soil Carbon Amendment Code 808. 5 pp.

Weber, K., and P. Quicker. 2018. Properties of biochar. Fuel. 217: 240 – 261.

Woolf, D., J.E. Amonette, F. A. Street-Perrott, J. Lehmann, and S. Joseph. 2010. Sustainable biochar to mitigate global climate change. Nature Communications. 1: 56.

Zhao, B., D. O'Connor, J. Zhang, T. Peng, Z. Shen, D.C.W. Tsang, and D. Hou. 2018. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. Journal of Cleaner Production. 174: 977 – 987.

Zhao, L., X. Cao, O. Masek, and A. Zimmerman. 2013. Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. Journal of Hazardous Materials. 256 – 257: 1 – 9.

APPENDICES

APPENDIX I – TGA RESULTS

Sample	Previously Dried	Initial Wt.	Moisture	Volatile Matter	Ash	Fixed Carbon	Volatile Matter Dry Basis	Ash Dry Basis	Fixed Carbon Dry Basis	Corrected Volatile Matter
JAKEW1W	No	1.872	63.91	6.642	4.51	24.94	18.4	12.49	69.1	6.642
JAKEW2W	No	1.407	56.46	7.371	9.233	26.93	16.93	21.21	61.86	7.371
JAKEW3W	No	1.345	59.68	7.251	4.775	28.3	17.98	11.84	70.18	7.251
JAKEW1D	Yes	1.357	0.9729	12.68	10.78	75.57	12.81	10.88	76.31	12.68
JAKEW2D	Yes	0.8636	1.123	14.21	11.49	73.18	14.37	11.62	74.01	14.21
JAKEW3D	Yes	1.407	1.031	13.89	11.35	73.72	14.04	11.47	74.49	13.89