

# **Biochar: An Overview**

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## **An Introduction to Pyrolysis, Biochar, and Biochar Production**

Every year, about 1.3 billion tons of biomass is available in the United States for bioenergy production (Perlack et al., 2005; Laird et al., 2009). Biomass is biological material derived from living, or once living organisms, including wood, crops, and plant waste, and animal/human feces. One of the ways to harness the energy available in biomass is through pyrolysis, which is the thermal decomposition of biomass in an environment with a negligible or limited supply of oxygen (Novak et al., 2009a).

Pyrolysis allows the transformation of low-energy-dense biomass into bio-oil (a high-energy-dense liquid), syngas (a low-energy-dense gas), and biochar (a carbon-rich high-energy-dense solid; Laird et al., 2009). Based on the desired product, the pyrolysis conditions can be optimized to favor the production of a specific one, with fast, gasification, and slow pyrolysis optimizing bio-oil, syngas, and biochar production respectively (Laird et al., 2009).

Bio-oil can be used directly in home heating devices, or further processed and used as transportation fuel, however current production costs exceed bio-oil's value (Braumakis et al., 2014). Syngas can be used for heating, but due to its low heating value, it is often burned to offset the energy cost of pyrolysis and is used to produce electricity or heat (Laird et al., 2009). Biochar has a variety of uses and has been used in the place of activated carbon, in water and waste filtration, for carbon sequestration, as fuel, applied to soils to enhance nutrient retention, improve crop productivity, improve the water holding capacity, reduce soil emissions, and improve the cation exchange capacity of soil (Lehmann & Joseph, 2009).

Rather than the composition or production method, it is the intended use that distinguishes biochar from charcoal, as biochar is produced for the application to soil, while charcoal which is produced for use in cooking and heating (Lehmann & Joseph, 2009). While the production method, feedstock, and chemical composition of biochar and charcoal would likely vary based on their intended use, little evidence or research has been found to determine the optimal unique production methods, feedstocks, and chemical compositions for these products (Lehmann & Joseph, 2009).

### **The History of Biochar**

The term biochar is relatively new in the literature, however, it has previously been studied and referenced under the terms “black lands,” “black earth,” “dark earth,” “*terra preta*,” “*terra preta du indio*” (Indian black earth in Portuguese), or Amazonian black earth (Kawa 2008; Hartt 1874a; Hartt 1874b; Smith 1879; Brown and Lidstone 1878).

Biochar was first referenced in the literature under the term *terra preta* in 1867 when Reverend Ballard S. Dunn wrote *Brazil: the Home for Southerners*. In his book Dunn encouraged other Confederates to migrate to Brazil rather than stay in the defeated South, and referenced the fertile dark land (*terra preta*) found in Brazil...

*The dark land, (Terra Preta) is found in some places apparently without admixture with vegetable elements, and in such situations has its color from some sulphurous or carbonaceous ingredient of the soil... the greatest part however of the dark land that is valuable for agricultural purposes... (Dunn 1866: 182-183).*

In an attempt to determine the soils fertility and origin, geologists began to travel to Brazil to study *terra preta*. As one geologist, Herber Smith documented...

*The cane-field itself is a splendid sight; the stalks ten feet high in many places, and as big as one's wrist. This is the rich terra preta, 'black land,' the best on the*

*Amazons. It is a fine, dark loam, a foot, and often two feet, thick. (Smith 1879: 144)*

While the fertility of *terra preta* was widely accepted, up until the 1900s the formation and composition of *terra preta* remained relatively unknown, and was often attributed to the activity of indigenous individuals (Kawa 2008; Niumendajú 2004). Studies conducted from the 1940's till today, however, have further confirmed this theory, with today's experts attributing *terra preta* formation to the actions of indigenous individuals who enriched their farmland with charred ash (Marris 2006).

This research gave evidence for the positive impact that charred organic matter could have on soil, and so the biochar initiative began.

### **The Production of Biochar**

To optimize biochar production a slow pyrolysis technique is often employed that uses temperatures ranging from 300-750°C, heating rates from 1-100°C/s, with pyrolysis durations ranging from minutes to hours (Cantrell et al., 2012; Spokas et al., 2011). As biochar can be produced using a variety of methods and feedstocks, its chemical composition and physical properties can vary widely, as can be seen in Table 1 (Smith et al., 2010; Amonette et al., 2008). Analyzing biochar from a single type of feedstock, the pyrolysis temperature, duration, and oxygen exposure all impact the quantity and quality of the biochar formed. However, despite this, there are trends in biochar production.

#### *Yield and Fixed Carbon Content*

In general as the peak pyrolysis temperature increases, the yield of biochar (by weight) decreases, however, the carbon content of the biochar (by weight) increases as the hydrogen, nitrogen, and oxygen present in the feedstock are released via the gaseous

phase (Mašek et al., 2013). Despite this trend, recent studies have found that low and high temperature pyrolysis produce near identical levels of stable recalcitrant carbon, as a higher stable carbon content product (of lower mass) is obtained during high temperature pyrolysis, while a lower carbon content product (of higher mass) is obtained during low temperature pyrolysis (Mašek et al., 2013). These results suggest that from a carbon sequestration standpoint, low and high temperature pyrolysis have negligible differences (Mašek et al., 2013). As can be seen in Table 1, however, it is important to note that the carbon content of the biochar can vary widely based on the feedstock selected.

#### *Nutrients and pH*

Feedstock nutrient (P, K, Ca, Mg) concentrations remain significantly higher when feedstocks undergo pyrolysis at higher temperatures (Gaskin et al., 2008), in addition, as pyrolysis temperature increases so does the alkalinity of the biochar (Hossain et al., 2011; Yuan et al., 2011; Cantrell et al., 2012). On the contrary, nitrogen concentrations often decrease as pyrolysis temperature increases as it is released into the gaseous phase (Gaskin et al., 2008). Depending on the desired nutrient (nitrogen vs. P, K, Ca, and Mg), pyrolysis temperature can be adjusted to optimize its concentration in the biochar.

Plant derived feedstocks often produce biochars of lower nutrient value due to the loss of nitrogen during the pyrolysis process, and the low nutrient values present in the initial feedstock (Cantrell et al., 2012). Due to the higher nutrient content in animal or human derived feedstock, nutrient concentrations in produced biochar often remain significantly higher (Cantrell et al., 2012). It is important to remember, however, that previous research has found that there are no statistically significant correlations between the nutrient quantity in the initial feedstock and the produced biochar. Therefore, initial

concentrations should not be used to predict biochar's nutrient quality (Cantrell et al., 2012).

#### *Surface Area and Absorption Capacity*

Increasing the pyrolysis temperature or exposure time increases the surface area and absorption capacity of biochar (Kearns et al., 2014; Cantrell et al., 2012). The removal of alkyl-CH<sub>2</sub>, ester C=O, aromatic -CO, and phenolic -OH groups from aromatic carbons, in addition to the loss of volatile organic matter that occurs at higher temperatures, is responsible for the subsequent increase in the surface area and micropore volume of biochar, as can further be seen in Table 1 (Chen et al., 2008; Lee et al. 2010; Ahmad et al., 2012).

#### *Reducing Water Content*

One of the greatest challenges when generating biochar from animal or human wastes is reducing the water content of the feedstock prior to pyrolysis to reduce external energy use consumption. For example, to make biochar from swine manure (very similar to human waste) at 97% moisture content requires 232.3 MJ/kg (Ro et al., 2010). However, by reducing the moisture content to 75%, the external energy required in the pyrolysis process decreases 19 fold (Ro et al., 2010). There are two strategies that are frequently employed to reduce the moisture content of the feedstock prior to pyrolysis. First, the feedstock can be left to air dry, put in a solar dryer, or put through another form of a pre-drying process. Second, the feedstock can be mixed with dried biomass (such as grass) and copyrolyzed with the feedstock, eliminating the need for external energy (examples of which can be seen in Table 1; Ro et al., 2010).

## **Uses of Biochar**

### **Activated Carbon**

#### *Precursor to Activated Carbon*

Activated carbon has a surface area that typically ranges from 500-1600 m<sup>2</sup>/g allowing it to be very useful in chemical reactions, filtration/purification, and absorption applications (Azargohar & Dalai, 2006). As biochar typically has surface areas ranging from 10-50 m<sup>2</sup>/g it is often used as a precursor for activated carbon. When used as a precursor, biochar is first treated with a strong acid or base and then heated to 500-1200 °C (Azargohar & Dalai, 2006). Temperature, chemical reagent choice, chemical reagent to biochar ratio, and nitrogen flow rate all impact the porosity development (Azargohar & Dalai, 2006; Tay et al., 2009). Previous researchers producing activated carbon through this method have created products that had up to 50 times the surface area of the starting material with surface areas as high as 1500 m<sup>2</sup>/g (Azargohar & Dalai, 2006).

#### *Water and Waste Filtration*

While many biochars range in surface area from 10-50 m<sup>2</sup>/g, specific feedstocks and heat treatments have produced biochars with surface areas comparable to that of low-grade activated carbon (without ever using an acid or base) achieving surface areas ranging from 10-1057 m<sup>2</sup>/g (Kearns et al., 2014). Able to achieve the surface area of activated carbon, biochar has been shown to be a cost effective alternative to activated carbon, and in some cases biochar has been found to be comparable or even out perform activated carbon in water/waste filtration (Kearns et al., 2014; Cao et al., 2009; Hale et al., 2011). With no base/acid treatment and pre/post activation process, biochar is substantially cheaper to produce, with the break even price of biochar estimated at US

\$246 per ton, compared to activated carbon at US \$1500 per ton (Ahmad et al., 2012; Klasson et al., 2009; McCarl et al., 2009).

When used in water/waste filtration not all biochars are equivalent, however, and the feedstock used to generate the biochar, in addition to the type of pyrolysis conducted, play key roles in determining the efficacy and type of organic and inorganic contaminants biochar can extract from water/wastewater. For a full review of biochars and their ability to remove organic (color/dyes, phenols, pesticides, polynuclear aromatics, and solvents) and inorganic (metal ions, anions) contaminants, please see the review conducted by Mohan et al., 2014.

While biochars do vary widely in their filtration abilities, some trends do emerge. In general as pyrolysis temperatures increase, so does the biochars ability to uptake/filter out contaminants (most likely from the subsequent increase in surface area; Kearns et al., 2014). Biochars produced from crop residues, peat, and wood are generally only effective at absorbing organic contaminants, while biochars produced from manures, however, are often very effective at absorbing organic, and inorganic contaminants due to their high phosphorous content, (although this is not the case for all manure derived biochars; Cao et al., 2009). Other researchers have found that biochars produced at lower temperatures are better at removing inorganic compounds as they contain a larger proportion of their original organic matter in the biochar (Kearns et al., 2014). Due to the retention of their original organic matter, however, low temperature biochars are often ineffective at removing pesticides and other compounds. While these biochars can initially absorb these compounds, these biochars often desorb the pesticides and other organic compounds as time progresses. This subsequent desorption has caused some

researchers to propose that these biochars could be used in pest and herbicide application, as it would avoid mass spraying and the aerosolization of toxic pesticides (herbicide applied to biochar, and then to field; Kearns et al., 2014; Li et al., 2013).

Due to biochars effectiveness in absorbing organic/inorganic contaminants, biochar is a logical option for applications in which high cost activated carbon would be unfeasible, such as storm drains, municipal water treatment, agricultural run off control, or water/wastewater treatment in low-income or rural areas (Kearns et al., 2014).

### **Soil Amendment**

While there are many studies that analyzed the effect of biochar addition on soil and crop productivity, the results vary widely. In terms of crop productivity, a meta-analysis conducted by Jeffery et al. found that across the fourteen studies analyzed there was a slight, statistically significant, positive impact on crop productivity across the studies, improving crop productivity/yield by 10%. Although the change in crop yield varied widely (-28 to +39%) the greatest improvements were often seen when biochar was added to acidic or neutral soils, and to those with medium/course textures (Jeffery et al., 2011). Biochar additions of 100 tons/hectare showed the greatest improvement in crop yield (+39%; Jeffery et al., 2011). It is important to note that other studies have documented increases in crop yields from +64% (Hossain et al., 2010), to +146% (Peng et al., 2011) to +250% (Van Zwieten et al., 2010), with the greatest improvements often seen when biochar was added in addition to fertilizer, with only modest improvements observed when added independently (Hossain et al., 2010; Van Zwieten et al., 2010; Peng et al., 2011).

Although the results vary widely, studies have also shown that biochar addition to soil can improve soil's: water retention ability (Karhu et al., 2011; Peng et al., 2011; Ding et al., 2010; Basso et al., 2013), pH (potential substitute for agricultural lime; Peng et al., 2011, Novak et al., 2009b; Collins, 2008; Galinato et al., 2011), cation exchange capacity (Peng et al., 2011; Van Zwieten et al., 2010), nutrient retention (Ding et al., 2010), and soil biota (Atkinson et al., 2010; Solaiman et al., 2010; Warnock et al., 2010), while reducing soil emissions (Karhu et al., 2011). However, it is known that pyrolysis temperature, pyrolysis duration, the initial feedstock, the amount of biochar added, and the initial chemical composition of the soil all impact biochars ability to positively impact the soil and crop yield. In addition, all of the previously cited studies have been conducted over a time period of months to two years, and no long-term studies have been done on the impact of biochar to soil (Jeffery et al., 2011). While biochar can effectively be used to eliminate soil contaminants (as discussed earlier), the wide spread adoption of biochar as a soil additive should not be done until more research is done on the pyrolysis conditions, feedstocks, initial soil qualities, and the amount of biochar that should be added to maximize biochars positive effect. Until these variables are optimized and long-term studies have been conducted, it is difficult to assess biochars value as a soil additive.

## **Carbon Sequestration**

### *Carbon Stability*

Biochar's carbon sequestration potential is rooted in biochar's carbon stability, which prevents the carbon present in biochar from immediately returning back to CO<sub>2</sub> or CH<sub>4</sub> through remineralization. The longer biochar can maintain its structure (higher

carbon stability) and prevent its carbon from re-entering the atmosphere, the greater role biochar can have in carbon sequestration plans. Often biochars carbon stability is measured by determining the half-life, or mean residence time of the carbon in the biochar. The half life refers to the amount of time it takes for half of the carbon present in the initial biochar to degrade (similar to a median), while the mean residence time refers to the average time that the carbon spends in the soil before it returns to the atmosphere (similar to the mean). The feedstock type, pyrolysis conditions, and the soil to which the biochar is added are all known to affect biochars half-life/mean residence time (Fang et al., 2014; Singh et al., 2012), and current studies have shown that biochar's mean residence time can vary from 44-2000 years depending on these conditions (Fang et al., 2014 [mean residence time: 44-610]; Kuzyakov et al., 2009 [mean residence time: 2000, half-life 1400]; Singh et al., 2012 [mean residence time: 90-1616]; Peng et al., 2011 [mean residence time: 244-1700]).

Singh et al. conducted a 5-year laboratory study that exemplifies how biochar's carbon stability can vary based on feedstock (Eucalyptus saligna wood and leaves, paper mill sludge, poultry litter, cow manure) and pyrolysis conditions. Using carbon-13 testing to determine the stability of the biochar, researchers found that 0.5-8.9% of the biochar was mineralized over the 5 year study period (Singh et al., 2012). Singh et al. found a wide range in the mean residence time of the biochar, ranging from 90-1600 years depending on the feedstock and pyrolysis conditions, as can be seen in Table 2 below. Biochars made from manure feedstocks, and biochars produced at lower pyrolysis temperatures had lower carbon stabilities (Singh et al., 2012).

Table 2: Carbon Stability of Biochar

<b>Feedstock</b>	<b>Temperature</b>	<b>Steam Activation</b>	<b>Carbon Mean Residence Time (years)</b>
Eucalyptus saligna wood	400°C	Yes	326
Eucalyptus saligna wood	400°C	No	294
Eucalyptus saligna wood	550°C	Yes	1271
Eucalyptus saligna wood	550°C	No	1616
Eucalyptus saligna leaves	400°C	Yes	270
Eucalyptus saligna leaves	550°C	Yes	572
Paper mill sludge	550°C	Yes	102
Poultry litter	400°C	No	129
Poultry litter	550°C	Yes	396
Cow manure	400°C	No	90
Cow manure	550°C	Yes	313

Note: Results adapted from Singh et al., 2012.

Ladygina & Rineau describe similar variations in biochar's half-life/mean residence time due to feedstock selection and pyrolysis conditions, reporting mean residence times that vary from 3-658 years based on the conditions. As biochar's carbon stability determines its carbon sequestration potential, the soil conditions, feedstock, and pyrolysis conditions must first be optimized before one can assess its carbon sequestration potential (Woolf et al., 2010).

### *Carbon Sequestration*

One of the proposed solutions to the increase in atmospheric concentrations of CO<sub>2</sub> and the continually rising levels of anthropogenic CO<sub>2</sub> emissions has been carbon sequestration through biochar production. Various researchers and biochar advocates have proposed that biochar production could offset national US greenhouse emissions by up to 12% annually (or about 1.8 PgCO<sub>2</sub>-C; Woolf et al., 2010) when the process is optimized for biochar production, and up to 10% annually when the process is optimized for bioenergy production, which is by far superior to other currently used carbon sequestration techniques.

Forestation, no tillage areas, and slash and burn practices have previously been used in an attempt to sequester carbon. However, while new forests can sequester a substantial amount of CO<sub>2</sub> initially, as these forests mature they begin to release as much CO<sub>2</sub> as they sequester (Lehmann 2007). Agricultural lands that are converted to no-tillage areas also sequester carbon initially, but after 10-15 years these areas encounter a similar phenomenon and begin to release as much CO<sub>2</sub> as they offset (Lehmann 2007). Used extensively worldwide, slash and burn land conversion only sequesters 2-3% of the initial carbon present in the biomass (due to the oxygen abundant burn conditions; opposed to roughly 30% with biochar), and only 0.2-0.6% of the carbon has been found to remain in the ground after 5-10 years (Atkinson et al., 2010).

The proposed carbon sequestration techniques through biochar production involve the mass pyrolysis of crop residues, animal manures, and forest residues on a national and/or global basis. As biochar can be produced at any level, from industrial to domestic production, biochar production can become a viable option independent of socioeconomic status (Woolf et al., 2010).

In order to sequester 12% of the global CO<sub>2</sub> emissions, Woolf et al. proposes a plan where 2.27 Pg-C (roughly 5 trillion lbs) of biomass would be converted to biochar annually. Obtaining biochar from waste sources, biochar production would not affect current land use or food production (for more information on the developed plan, please see Woolf et al., 2010).

Other variations of carbon sequestration techniques through biochar production emphasize fuel displacement. By optimizing bioenergy production in the biochar production process, researchers estimated that by harvesting 1.1 billion tons of biomass

from US crop lands, one could offset 25% of the US's fossil fuel consumption. Through fossil fuel displacement, biochar production, and carbon sequestration, it was estimated that this technique could offset about 10% of the annual US CO<sub>2</sub> emissions (Galinato et al., 2011; Laird 2008).

In order for biochar sequestration techniques to be successful, the biomass cannot be obtained from land clearance, food sources, or created in in-efficient burners. Land clearance cannot be a part of generating feedstocks for biochar production as this destroys valuable ecosystems and releases carbon stored in biomass and soil, "...leading to carbon payback times in excess of 50 years"(Woolf et al. 2010:3). Agricultural lands used for food production cannot be transferred to biomass crops for biochar production, as this would negatively impact food security and stimulate land clearing in other locations (Woolf et al., 2010). Finally, modern pyrolysis technology (low emissions, high biochar yield) would have to be used in the biochar production process, as the emissions from inefficient biochar units can quickly negate any benefits.

Before any of these plans could be implemented however, more research will need to be conducted on the carbon stability of biochar, and the ways in which the pyrolysis conditions and feedstock can be used to optimize biochar's carbon stability. As biochar's carbon sequestration is based upon biochar's ability to slow carbons release into the atmosphere, biochar's carbon stability must first be optimized before one can assess its carbon sequestration potential (Woolf et al., 2010).

In-order to allow biochar to be an economically feasible option for carbon sequestration, biochar production must first be recognized by a carbon market as an accepted carbon sequestration technique. Currently, under the Kyoto Protocol developed

by the United Nations Framework on Climate Change (UNFCCC), biochar does not qualify as an accepted carbon sequestration method (Galinato et al., 2011). Until national or global carbon markets recognize biochar, it is unlikely that biochar will be an economically feasible option for agricultural soil amendment or climate change mitigation (Galinato et al., 2011).

### **Biochar and Human Waste**

The conversion of human waste to biochar has applications in both developing and developed countries.

In developing countries biochar production technology is driven primarily by the need for sanitation and energy production rather than the associated benefits of biochar. In 2013, 2.5 billion individuals did not have access to proper sanitation services, and of those approximately 1 billion practiced open defecation. This represents a major public health concern as improper sanitation services and open defecation allow bacteria, parasites, and viruses present in human waste to contaminate water, food, and soil (WHO 2008). This can lead to cholera, hepatitis, polio, worm infestation, and diarrhea. In fact, water contamination from human waste is one of the leading causes of diarrhea worldwide, and the second leading cause of death for children in developing countries (WHO 2008). One of the proposed solutions to alleviate this problem has been to convert raw human waste into biochar. This has been proposed for a variety of reasons, including: 1) due to the high temperatures achieved in pyrolysis process, all pathogens and organic toxins present in the human waste would be destroyed (Laird et al., 2009); 2) pyrolysis provides a method for significantly reducing waste stream volume (Cantrell et al., 2012; see Table 1); 3) pyrolysis of human waste provides a net energy output, which

could be used to generate heat or electricity in rural or low-income applications (Liu et al., 2014); and 4) pyrolysis creates an end value-added usable product, biochar, which could be used in any of the applications previously mentioned in this paper, including fuel (Cantrell et al., 2012).

From an energy standpoint, human waste can vary widely in energy content from 12.4-18.12 MJ/kg, presumably due to variation in diet and the moisture content (Zanoni & Mueller, 1982; Liu et al., 2014). Despite this variation, when human waste (at 18.12 MJ/kg) undergoes pyrolysis at moisture levels below 57% a biochar pyrolysis unit can harvest the produced biochar and still have a net energy output in the form of heat or electricity (Liu et al., 2014). This energy output can be increased by employing a solar (or other method) pre-dryer to obtain feedstock with moisture levels below 57%, or by using the biochar for fuel (Liu et al., 2014). Working in developing countries Ward et al., has developed a method of creating briquettes made with 10% starch and 90% biochar from human waste that an energy content of 25 MJ/kg, comparable to that of charcoal. These briquettes could then be used for home heating or cooking applications in rural and/or low-income communities.

In contrast to the needs in developing countries, biochar technology in developed countries is primarily focused around waste reduction, and the generation and use of the final biochar product. Due to the availability of other feedstocks for these purposes, however, few units have been designed in developed countries for the pyrolysis of human waste.

## **Biochar uses in Food and Medicine**

As of 2014, there have been no studies conducted to evaluate biochar's role in food and medicine. While biochar remains a key ingredient in many herbal treatments and supplements, biochar's effectiveness has yet to be proven scientifically in these applications. Used as a low-grade activated carbon, however, biochar could have future uses in medicine, particularly in rural and low-income areas where activated carbon is not readily available, although further research would need to be conducted to support this use.

Due to activated carbon's high absorption properties, activated carbon is regularly used in medicine to remove various drugs or toxins from the gastrointestinal system, and has been shown to be more effective at drug/toxin elimination than stomach pumping (Neuvonen & Olkkola, 1988). Activated carbon can help eliminate toxins even after systematic absorption, although it is most effective at absorbing toxins and drugs present in the stomach at the time of consumption, and to maximize effectiveness, activated carbon must be taken as soon as possible after intoxication. Activated carbon cannot absorb alcohol, cyanide, and specific heavy metals, such as lithium and iron (Neuvonen & Olkkola, 1988).

## **The Safety of Biochar Production and Use**

There are three safety concerns that occur when producing and using biochar.

First, as biochar is produced under a negligible or limited supply of oxygen, pyrolysis units by definition are undergoing incomplete combustion and there is a potential that these units could emit high levels of particulate matter and other pollutants. Technology currently developed for heating biomass combustion products could be

applied to this technology, however, and further reduce/eliminate this problem (Hallowell 2014). Currently unregulated at the national level, in November of 2014 the EPA defined biochar for the first time in the “*Framework for Assessing Biogenic CO<sub>2</sub> Emissions from Stationary Sources*” where they recognized biochar production as a potential source for significant air pollution. While there are currently no emissions regulations in place at the federal level for biochar production units, as the use and production of biochar continues to expand they will likely be developed/enforced.

Second, the biochars produced by some pyrolyzers (specifically fast pyrolyzers) are produced as fine powder, and if stored or produced in an area with exposure to oxygen and moisture, pose a significant explosive hazard (Laird et al., 2009).

Third, the application of biochar to soil for agricultural purposes will cause significant particulate matter production, which could harm those working and living near the agricultural sight (Laird et al., 2009). Researchers have posed that by producing biochar in slurry, or by mixing it with water or manure, the explosive and particulate matter safety concerns (that occurred when spreading it) could be eliminated (Laird et al., 2009).

### **Further Research**

This paper has identified a number of areas in which further research into biochar and its uses have yet to be done.

Before widely adopting biochar as a means of carbon sequestration, more research needs to be done to understand the carbon stability of created biochars, and to determine the feedstocks and pyrolysis conditions that optimize its carbon lifespan.

While biochar can effectively be used to eliminate soil contaminants, the wide spread adoption of biochar as a soil additive should not be done until more research is done on the pyrolysis conditions, feedstocks, initial soil qualities, and the amount of biochar that should be added to maximize biochars positive effect. Until these variables are optimized and long-term studies have been conducted, it is difficult to assess biochars value as a soil additive.

Two studies have found that biochar can be a significant source and retainer of polycyclic aromatic hydrocarbons (PAHs) and more research needs to be conducted to determine the feedstocks and pyrolysis conditions that minimize PAH concentrations before biochars widespread acceptance/addition to soil (Keiluweit et al., 2012; Quilliam et al., 2013). This is of upmost concern as Keiluweit et al. found biochars that greatly exceeded the EPA maximum allowable levels of PAHs for biosolids applied to agricultural lands (Keiluweit et al., 2012). While pyrolysis temperatures greater than 600°C minimize concentrations of PAHs, more research needs to be conducted on the feedstocks and pyrolysis conditions that factor into PAH production and retention (Keiluweit et al., 2012).

## **Conclusion**

Biochar has many current and theoretical future applications. Among the current uses of biochar lies its great-untapped potential for use as a fuel source, low-grade activated carbon, and mechanism for human waste disposal. The biochar production process has been shown to be an effective way to generate renewable electricity, heat, liquid bio-oil, syngas, and biochar. Due to biochars effectiveness in absorbing organic/inorganic contaminants, biochar is a logical option for applications in which high

cost activated carbon would be unfeasible, such as storm drains, municipal water treatment, agricultural run off control, or water/wastewater treatment in low-income or rural areas. In the disposal of human waste, the biochar production process can effectively: 1) destroy all the pathogens and organic toxins present; 2) significantly reduce waste stream volume; 3) provide a net energy output; and 4) create an end usable product, which could be used for any of the applications previously mentioned.

Although biochar is currently marketed as a carbon sequestration technique and soil additive, there is not enough scientifically backed evidence to support the widespread adoption of biochar for these uses at this time. Before being implemented as a carbon sequestration technique, more research needs to be conducted to optimize the pyrolysis conditions and feedstock properties that optimize its carbon stability. While biochar's addition to soil *generally* improves crop yield, water retention, cation exchange capacity, and healthy soil biota, not all additions of biochar to soil produce positive effects, with some biochar additions negatively impacting the soil in all of these areas. In addition, the concentrations of biochar needed to obtain maximum soil effects (e.g. 100 tons/hectare) would not be cost effective for agricultural purposes. While some would argue that biochar addition could be cost effective alternative over time, no studies have currently evaluated biochar's impact to soil past the two-year mark. Future research needs to be done to determine the feedstocks, pyrolysis conditions, initial soil compositions, and the amount of biochar that needs to be added to maximize the longevity and the efficacy of biochars addition to soil.

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Table 1:

Feedstock	% Moisture	Pyrolysis Temp	Biochar Yield wt%	Stable carbon yield	Surface area m <sup>2</sup> /g	pH	Other	Citation
Corn Cob	11.7%	300°C	77.3%	49.1%	61.8	8.1		Liu et al., 2014
Corn Cob	11.7%	400°C	36.9%	71.7%	180.1	9.1		Liu et al., 2014
Corn Cob	11.7%	500°C	23.3%	81.6%	212.6	9.3		Liu et al., 2014
Corn Cob	11.7%	600°C	21.7%	82.4%	192.9	10.4		Liu et al., 2014
Corn Stalk	8.4%	500°C	30.9%	76.6%	201.3	10.1		Liu et al., 2014
Corn Stover	Dried and ground, <10%	500°C	33.2%	54.7%	20.9		Nitrogen purge 1L/min 50g for 30m	Brewer et al., 2009
Corn Stover	Dried and ground, <10%	500°C	n/a	34.4%	7.0		Performed on a 5kg/h capacity bubbling fluidized bed reactor	Brewer et al., 2009
Corn Stover	Dried and ground, <10%	730 °C	n/a	38.5%	23.9		3 kg/h capacity bubbling fluidized bed reactor using an air/nitrogen fluidizing gas	Brewer et al., 2009
Dairy Manure	Dried 0.31%-6.49%	350 °C	54.9%	23.2%	1.64	9.2	Nitrogen purge 1L/min	Cantrell et al., 2012
Dairy Manure	Dried 0.31%-6.49%	700 °C	35.0%	34.7%	186.5	9.9	Nitrogen purge 1L/min	Cantrell et al., 2012
Feedlot Manure (manure with cornstalk bedding)	Dried 0.31%-6.49%	350 °C	51.1%	23.5%	1.34	9.1	Nitrogen purge 1L/min	Cantrell et al., 2012

Feedlot Manure	Dried 0.31%-6.49%	700 °C	32.2%	36.3%	145.2	10.3	Nitrogen purge 1L/min	Cantrell et al., 2012
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Table 1: (cont).

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Goat Manure	Oven dried, 8.7%	400 °C	44.5%	31% est.	3.27			Touray et al., 2014
Goat Manure	Oven dried, 8.7%	500 °C	40.6%	36% est.	1.68			Touray et al., 2014
Goat Manure	Oven dried, 8.7%	600 °C	37.9%	38% est.	13.92			Touray et al., 2014
Goat Manure	Oven dried, 8.7%	700 °C	35.5%	36% est.	39.08			Touray et al., 2014
Goat Manure	Oven dried, 8.7%	800 °C	33.8%	35% est.	93.49			Touray et al., 2014
Mixed larch and spruce wood chips	30%	350 °C	44% est.	72% est.				Masek et al., 2013
Mixed larch and spruce wood chips	30%	450 °C	36% est.	78% est.				Masek et al., 2013
Mixed larch and spruce wood chips	30%	550 °C	30% est.	86% est.				Masek et al., 2013
Paper mill Waste		550 °C	32%	50%	114.9	9.4	32.6% (by mass) enhanced solids reduction (ESR) sludge, 18.8% clarifier sludge and 48.6%	Van Zwieten et al., 2010

							waste wood chips	
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Table 1: (cont).

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Paper mill Waste		550 °C	29%	52%	114.9	8.2	19.5% ESR sludge, 11.2% clarifier sludge and 69.3% waste wood chips	Van Zwieten et al., 2010
Peanut Shells	Dried, % n/a	300 °C	36.91%	68.27%	3.14	7.76		Ahmad et al., 2012
Peanut Shells	Dried, % n/a	700 °C	21.89%	83.76	448.2	10.58		Ahmad et al., 2012
Peanut Shells	n/a	400°C	n/a	73.2%	n/a	10.5		Gaskin, et al., 2008
Peanut Shells	n/a	500°C	n/a	80.4%	n/a	10.1		Gaskin, et al., 2008
Peanut Shell	Air dried, n/a	400°C	40%	59%	0.52	7.9	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Peanut Shell	Air dried, n/a	500°C	35%	56%	1.22	8.6	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Pecan Shell	Air dried, n/a	350 °C	50%	62%	1.01	5.9	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b

Pecan Shell	Air dried, n/a	700 °C	30%	53%	222	7.2	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
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Table 1: (cont).

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Pine Chips	43%	350 °C	42% est.	71% est.				Masek et al., 2013
Pine Chips	43%	450 °C	31% est.	77% est.				Masek et al., 2013
Pine Chips	43%	550 °C	30% est.	84% est.				Masek et al., 2013
Pine Chips	n/a	400°C	n/a	73.9%	n/a	7.55		Gaskin, et al., 2008
Pine Chips	n/a	500°C	n/a	81.7%	n/a	8.30		Gaskin, et al., 2008
Poultry Litter	10.2%	620°C	44% est.	30.8%	n/a			Ro et al., 2010
Poultry Litter	Air dried, n/a	350 °C	57%	72%	1.10	8.7	Pyrolysis with nitrogen, done with pelletized litter	Novak et al., 2009b
Poultry Litter	Air dried, n/a	700 °C	36%	44%	9.00	10.3	Pyrolysis with nitrogen, done with pelletized litter	Novak et al., 2009b
Poultry Litter	n/a	400°C	n/a	39.2%	n/a	10.1		Gaskin, et al., 2008
Poultry Litter	n/a	500°C	n/a	39.2%	n/a	9.74		Gaskin, et al., 2008

Poultry Litter	Dried 0.31%- 6.49%	350 °C	54.3%	27.0%	3.93	8.7	Nitrogen purge 1L/min	Cantrell et al., 2012
Poultry Litter	Dried 0.31%- 6.49%	700 °C	36.7%	35.5%	50.9	10.3	Nitrogen purge 1L/min	Cantrell et al., 2012

Table 1: (cont.)

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Rice Straw	n/a	250 °C	53.7%	63.5%				Peng et al., 2011
Rice Straw	n/a	300 °C	46.2%	67.6%				Peng et al., 2011
Rice Straw	n/a	350 °C	38.9%	66.2%				Peng et al., 2011
Rice Straw	n/a	400 °C	34.6%	69.7%				Peng et al., 2011
Rice Straw	n/a	450 °C	31.9%	72.9%				Peng et al., 2011
Saw Dust	9.9%	500°C	22.6%	80.6%	243.1	9.5		Liu et al., 2014
Softwood Pellets	6%	350 °C	38% est.	72% est.				Masek et al., 2013
Softwood Pellets	6%	450 °C	31% est.	78% est.				Masek et al., 2013
Softwood Pellets	6%	550 °C	28% est.	84% est.				Masek et al., 2013
Soybean Stover	Dried, % n/a	300 °C	37.03%	68.81%	5.61	7.27		Ahmad et al., 2012
Soybean Stover	Dried, % n/a	700 °C	21.59%	81.98%	420.3	11.32		Ahmad et al., 2012
Swine Solids	Dried	350 °C	62.3%	17.7%	0.92	8.4	Nitrogen purge 1L/min	Cantrell et al.,

	0.31%- 6.49%							2012
Swine Solids	Dried 0.31%- 6.49%	700 °C	36.4%	33.8%	4.11	9.5	Nitrogen purge 1L/min	Cantrell et al., 2012
Swine Solids	Dried, 12.8%	620°C	35% est.	41.2%	n/a			Ro et al., 2010
Swine Solids blended (29% rye and 71% swine solids, w/w)	Dried, 10.9%	620°C	30% est.	51.6%	n/a			Ro et al., 2010

Table 1: (cont.)

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Solid Fraction of anaerobically digested pig manure (SADPM)	Dried at 60°C for 48 hours, 8.5%	600°C	43.2%	26.2%	17.0	9.3	Nitrogen flow rate 50 cm <sup>3</sup> min <sup>-1</sup>	Troy et al., 2013
SADPM mixed 4:1 (w/w) with sawdust	Dried at 60°C for 48 hours, 7.0%	600°C	32.1%	42.3%	19.4	9.0	Nitrogen flow rate 50 cm <sup>3</sup> min <sup>-1</sup> Addition of sawdust significantly decreased biochar yield.	Troy et al., 2013
SADPM mixed 3:2 (w/w) with sawdust	Dried at 60°C for 48 hours, 7.4%	600°C	30.6%	56.1%	24.4	8.9	Nitrogen flow rate 50 cm <sup>3</sup> min <sup>-1</sup> Addition of sawdust significantly decreased	Troy et al., 2013

							biochar yield.	
Composed SADPM	Dried at 60°C for 48 hours, 9.0%	600°C	49.3%	23.3%	14.2	9.4	Composing reduced 50% mass content, 15% water. Nitrogen flow rate 50 cm <sup>3</sup> min <sup>-1</sup>	Troy et al., 2013
Composed SADPM mixed 4:1 (w/w) with sawdust	Dried at 60°C for 48 hours, 6.2%	600°C	39.1%	37.2%	17.4	9.5	Addition of sawdust significantly decreased biochar yield. Nitrogen flow rate 50 cm <sup>3</sup> min <sup>-1</sup>	Troy et al., 2013

Table 1: (cont.)

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Composed SADPM mixed 3:2 (w/w) with sawdust	Dried at 60°C for 48 hours, 5.8%	600°C	34.5%	54.7%	23.2	8.7	Nitrogen flow rate 50 cm <sup>3</sup> min <sup>-1</sup> Addition of sawdust significantly decreased biochar yield.	Troy et al., 2013
Switchgrass	Dried and ground, <10%	500°C	41.0%	39.5	50.2		Nitrogen purge 1L/min 125g for 2 h	Brewer et al., 2009
Switchgrass	Dried and ground, <10%	500°C	n/a	26.4%	21.6		Performed on a 5kg/h capacity bubbling fluidized bed reactor	Brewer et al., 2009
Switchgrass	Dried and ground,	760 °C	n/a	34.3	31.4		3 kg/h capacity bubbling fluidized bed reactor using	Brewer et al., 2009

	<10%						an air/nitrogen fluidizing gas	
Switchgrass	Air dried, n/a	250 °C	78%	89%	0.40	5.4	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Switchgrass	Air dried, n/a	500 °C	29%	51%	62.2	8.0	Pyrolysis with nitrogen, ground to pass through 1-2 mm sieve before pyrolysis	Novak et al., 2009b
Turkey Litter	Dried 0.31% - 6.49%	350 °C	58.1%	23.1%	2.60	8.0	Nitrogen purge 1L/min	Cantrell et al., 2012
Turkey Litter	Dried 0.31% - 6.49%	700 °C	39.9%	29.2%	66.7	9.9	Nitrogen purge 1L/min	Cantrell et al., 2012

Table 1: (cont.)

<b>Feedstock</b>	<b>% Moisture</b>	<b>Pyrolysis Temp</b>	<b>Biochar Yield wt%</b>	<b>Stable carbon yield</b>	<b>Surface area m<sup>2</sup>/g</b>	<b>pH</b>	<b>Other</b>	<b>Citation</b>
Urban Wastewater Sludge	7.6%	300°C	72.3%	Carbon: 25.6% FC: 9.1%		5.32		Hossain et al., 2011
Urban Wastewater Sludge	7.6%	400°C	63.7%	Carbon: 20.2% FC: 6.8%		4.87		Hossain et al., 2011
Urban Wastewater	7.6%	500°C	57.9%	Carbon: 20.3%		7.27		Hossain et al., 2011

Sludge				FC: 7.6%				
Urban Wastewater Sludge	7.6%	700°C	52.4%	Carbon: 20.4% FC: 8.3%		12.00		Hossain et al., 2011