Comparison of Biochar Characteristics from Different Production Scales

USDA Forest Service - Wood Innovations Project (23-DG-11094200-453).

The Northern MN Closed Cycle Biochar Pilot; A Collaborative project with Dovetail Partners, Minnesota Power and the Carlton Soil and Water Conservation District

by Dovetail Partners Associate: Harry Groot

Published by Dovetail Partners August 2025

Project Description

The project was inspired as a way to reduce increasing wildfire fuels in northern Minnesota, by demonstrating potential markets for that woody biomass. The region's forest products industry's decline has exacerbated this need, resulting in aging and overstocked forests. Producing biochar is a promising market opportunity, simultaneously providing climate, ecological, and soil health benefits by converting wildfire reduction, habitat restoration, or invasive biomass into a useful product.

The project's at-scale field trials over three growing seasons, were designed to demonstrate the soil health value of agricultural biochar applications. This report, however, will focus on a second objective: comparing biochar from commercial and smaller-scale efforts. Details about the field trials are available in the Project's initial Storymap and there will be report(s) available about field trial results at the project's conclusion.

(Visit StoryMap Here!)

What is Biochar?

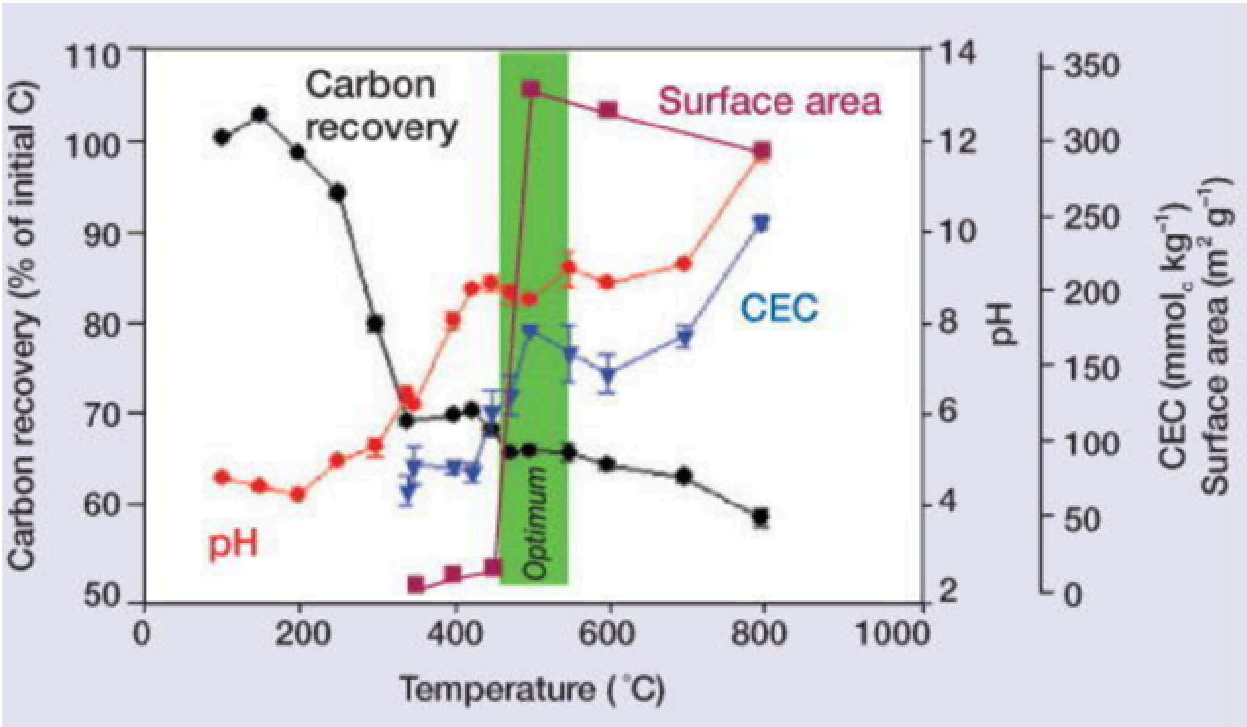
Biochar is made from a variety of feedstocks via pyrolysis: an irreversible thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen.

The biochar used in this project was produced by Seneca Farms Biochar[1] at two different temperatures on "either side" of the "sweet spot" shown in Figure 1.

[1] https://sfbiochar.com/

This graph is typical of the production of biochars from most feedstocks in that there is a marked increase in the carbon infrastructure's surface area around 400 to 500C in concert with substantial changes in other properties.

Figure 1. The "Sweet Spot" for Optimum Biochar Production Temperatures



Source: Lehmann, J. (2007), Bio-energy in the black. Frontiers in Ecology and the Environment, 5: 381-387. https://doi.org/10.1890/1540-9295(2007)5[381:BITB]2.0.CO;2

Comparing Biochars

A note on the comparison shown in the tables below: The data used is from a collection of donated data from a variety of sources (feedstocks, production technologies, process parameters, and operators), to compare and draw some broad conclusions. For simplicity, averages have been used in the tables below for the 10 pilot plant scale operations, three commercial operations, and 11 place-based samples, also known as do-it-yourself, or Biochar On Site (BOS). The full data set is available here.

This report will use explanations from the USBI fact sheet "INTERPRETING BIOCHAR LAB REPORTS" about the individual characteristics from the analyses' breakdown.[2]

[2] USBI Fact Sheet

The analyses were all run by Control Labs, Inc.[3] in Watsonville, CA in accordance with the IBI (International Biochar Initiative) Standards at the time (2023). The low cost proximal analyses do not test for some characteristics (like the metals and nutrients), and both test options were sampled to determine if the cost savings was justified.

Biochars' Characteristics

Table 1. Biochars' Characteristics

	Organic Carbon	Hydrogen /Carbon (H:C)	Total Ash	pH	Liming (neut. Value as-CaCO3)	Carbonates (as-CaCO3)	Volatile Matter	Electrical Conductivity	Surface Area Correlation
Production Scale	**Dry %**	**Molar Ratio**	**Dry %**		**%**	**%**	**% dry wt.**	**dS/m**	**m2/g**
Pilot	66.59	0.82	6.97	6.71	5.61	1.24	49.32	0.58	208.50
Commercial	83.65	0.29	7.71	8.58	7.13	4.28	16.35	0.50	388.25
BOS	77.08	0.39	11.40	8.83	14.31	7.86	16.28	0.75	238.00
Proximal	79.90	0.30	11.03			6.98	18.93		267.00

Source: BOS-Commercial Report version.xlsx

Bulk density (not shown in this table)

Bulk density is a required value to allow conversion between volume-based units (such as cubic meters or yards) and weight-based units (e.g., Kg or tons). The mass of biochar per unit is substantially lower than the bulk density of soil. When applied to soils, biochar typically reduces soil bulk density.

Very little difference was seen between the different production technologies, however the range in each set was similar—ranging from 8 to 24 lbs/ft^3. As would be expected, the commercial biochars showed the least variation, but they were all made from softwood feedstocks where the Pilot and BOS runs were with a variety of feedstocks, including switchgrass, softwoods, hardwoods, nut hulls, and mixed brush from invasive removal, habitat restoration, and fire reduction efforts.

Organic carbon (Corg) and carbonates (as CaCO3)

Total carbon analysis measures both organic carbon and inorganic carbonates, the latter of which is contained in the ash fraction (typically in the form of carbonates).

[3] Biochar Testing - Watsonville, CA - Control Laboratories

This report separates total carbon into organic carbon (Corg) and carbonates (as $CaCO_3$). For all feedstocks, Corg generally increases with increasing production temperature.

The carbon sequestration potential of biochar is directly related to Corg, and this analysis is required under all existing carbon removal methodologies for biochar and for use as a soil amendment under USDA incentive payment programs for biochar such as USDA Natural Resources Conservation Service (NRCS) Conservation Practice Standard (CPS) 336.[4] Manure and grass biochars tend to be lower in Corg than wood-derived biochars.

Despite the fact the table shows a marked difference between the Pilot and the other technologies, out of the 10 pilot-scale samples, six were "undercooked" and had carbon contents in the 50% range and one grass-based biochar was only 66% carbon. The rest were pyrolyzed more thoroughly and had 80 to 90% carbon content. This variation in biochars illustrates why testing is important to match a given biochar to its intended application. In some cases, a lower carbon content with commensurate increase in other characteristics, might be preferred to a higher carbon biochar.

The commercial biochars were very consistent, with samples coming from deliveries which were in the hundreds of cubic yards. Verification samples confirmed this consistency.

The BOS samples also showed a broad consistency across a variety of (woody) feedstocks. Woody feedstocks are the most common for flame-capped kilns (which description includes both the Oregon and Ring of Fire® technologies.)

Noting that with the producers of any commercial commodity product, consistency is critical. And to produce a consistent end product, the manufacturing process has to be stable and dependable. Commercial biochar production is a process which depends on generating volumes of a consistent product where the feedstocks and processing conditions are monitored and managed. In contrast, BOS production has more uncontrolled variables; for instance, it's a mobile batch process influenced by ambient conditions and the feedstock (size, amount of decay, moisture content, species). However, despite this, the larger data set shows the BOS is capable of generating a relatively consistent product.

The pilot process biochars had high variability because those systems are intended to be able to manage the process to generate products with different characteristics. That management flexibility is beneficial at that scale; however, it can also be a problem if it's difficult to maintain consistent operating conditions (like maintaining stable temperatures or feed rates—which result in under pyrolyzed biochars seen in samples 5-9.)

[4] NRCS 336: Soil Carbon Amendment (Ac.) (336) Conservation Practice Standard | Natural Resources Conservation Service

H:C ratio and fixed carbon

The ratio of hydrogen (H) to carbon (C) atoms, abbreviated as H:Corg (sometimes reported as Corg, H:C, or H/C), is an indicator of biochars' stability. Lower H:C ratios generally correspond to stronger bonds between carbon atoms, reducing susceptibility to microbial and chemical decomposition, therefore indicating a greater long-term carbon sequestration potential. Many biochar standards and carbon removal methodologies require an H:C ratio less than 0.7.

The Commercial and BOS biochars consistently had lower H:Corg ratios, probably due to the higher process temperatures, which should have larger stable Carbon fractions resulting in longer lasting carbon than the lower temperature Pilot scale material.

Total ash

The ash fraction of biochar contains mineral carbonates and oxides that can react in soil to increase pH, provide nutrients to plants, and bind metals and phosphorus. The ash fraction is composed of elements that do not volatilize (calcium, potassium, magnesium, silicon, phosphorus and trace metals) at typical biochar production temperatures.

For this characteristic, the control of the process is evident in the lower ash content of the Pilot and Commercial biochars. The BOS chars' higher ash content is consistent with the flame capped technology where there is minimal control of the process. However, for use in acidic soils, this can be an advantage as can be seen with the pH and liming capability.

pH and Liming

Biochars generally have alkaline pH (above pH 7), but acidic and neutral pH biochars can also be produced under certain production conditions. As the ash fraction of the biochar increases, salts, oxides, hydroxides, silicates, and carbonates also increase, which contributes to biochar alkalinity.

Biochar pH does not directly describe the potential of biochar to change the pH of soils. Soils have pH buffering capacity that allows soils to resist pH changes. Liming equivalent estimates biochar's ability to impact the pH of soil, soilless media, and other media blends.

The various samples are consistent with the higher pH and liming capacity with higher ash content. It's notable that the current proximal testing regimen does not include pH, however this is an easily measured characteristic at low cost. .,

Volatile matter

Volatile matter is composed of compounds that volatize from the biochar in the absence of oxygen at 950 °C. Volatile matter may contain gases like carbon monoxide and methane; organic hydrocarbons, acids, and tars; and some inorganic compounds. Volatile matter can be an important food source for microbes, which can improve soil fertility.

The volatile matter was fairly consistent between the various samples at all scales, with the exception of the lower carbon Pilot samples.

Electrical conductivity

Electrical conductivity (EC) measures soluble salt content in biochar. A low EC indicates that biochar is low in soluble salts and vice versa. The impact of biochar salts on salinity is typically short-lived in applications where water percolates through media. That is the case in stormwater treatment, nursery and seedling production, and most farming except in drier regions. Intentionally rinsing biochar with fresh water can be used to reduce biochar EC. High amounts of salt can cause plant toxicity, especially in seedlings, transplants, and nursery crops. However, high EC may indicate that the biochar has high levels of plant nutrients, so higher EC biochar may be a good choice for established crops.

The Electrical Conductivity of the biochars was relatively consistent in the Pilot and Commercial biochars using similar feedstocks, but were higher in the BOS samples. This may be due to the flood quenching technique used in BOS kilns to stop pyrolysis. A closer look at the entire data set is instructive, to note the high EC of a grass feedstock and generally lower ECs with woody feedstocks.

Surface area

Surface area, typically reported in square meters per gram (m2/g), indicates the total area of the biochar surface. Biochar with high surface area typically has greater potential to absorb environmental toxins, metals, and nutrients, so the surface area of biochar is especially important when used in environmental remediation applications. The surface area of biochars used in soil are important to indicate the char's capacity to retain moisture and nutrients, as well as to bind pollutants.

In these samples, the Commercial biochars had consistently higher surface areas, but the BOS biochars were consistent, too, just lower. Better process control in commercial systems undoubtedly yields a "better" more consistent product. However, the BOS biochars are probably adequate for soil applications where low costs and removal of "offensive" material provides the feedstocks. These tradeoffs offer another example of knowing the biochars' characteristics to match with specific applications.

Table 2. Elemental Properties (Heavy Metals and Micronutrients)

Arsenic	**Cadmium**	**Chromium**	**Cobalt**	**Copper**	**Lead**	**Molybdenum**	**Mercury**
Nickel	**Selenium**	**Zinc**	**Boron**	**Chlorine**	**Sodium**	**Iron**	**Manganese**

Source: BOS-Commercial Report version.xlsx

Many biochar standards require that it be analyzed for a broad suite of metals, especially for soil applications. The IBI and, in the USA, NRCS guidelines for biochar include a range of maximum allowable concentrations for metals based on a review of regulatory values. However, state and local regulations may be more stringent. Many state departments of agriculture also maintain standards for heavy metal application rates via soil amendments, typically expressed as limits on total metals mass applied per acre.

Some metals (e.g., arsenic, chromium, mercury) are phytotoxic and/or pose human health hazards, while other metals are plant micronutrients (e.g., nickel, zinc, boron) and contribute to the growth and health of crops.

Due to the amount of data and the relatively low elemental levels, averages are not shown here, but are available in the comprehensive spreadsheet. The levels of all the elements tested were below the listed thresholds; however, there were notable differences in some elements depending on feedstock and processing temperature. Proximal analysis does not include elemental data.

Nutrients

Table 3. Soil Enhancement Properties

	Soil Enhancement Properties (% Dry Weight)					
Production Scale	**Total Nitrogen (N)**	**Total (P)**	**Total (K)**	**Ammonia**	**Nitrate**	**Organic N**
Pilot	0.64	0.08	0.59	0.00	0.00	0.63
Commercial	0.63	0.13	0.65	0.00	0.00	0.62
BOS	0.72	1.07	0.16	0.00	0.00	0.72
PROXIMAL	0.56					

Source: BOS-Commercial Report version.xlsx

Nutrient data is provided for informational purposes, which is useful for biochar destined to be used in soil. As can be seen in the averages in Table 3 the amount of NPK is minimal in all biochars processed from grass and woody feedstocks.

In these samples, the BOS biochars were somewhat better in their NPK contributions than either the Commercial or Pilot scale biochars. There are techniques to improve these levels which will be discussed further in the Summary.

Total potassium (K)

Biochar produced from certain feedstocks, such as manure, can contain substantial amounts of potassium (K). Potassium in biochar is readily available to plants and can meet a portion of crop potassium needs.

Total phosphorus (P)

The P found in biochar is generally present as calcium and magnesium-phosphate complexes. In these forms, biochar can act like a slow release fertilizer, and allow plants to uptake available P. Their availability depends on which phosphate compounds are present in biochar but also on inherent soil properties, such as the mineralogy of the soil and dynamic soil properties, like pH. Some studies have shown that applying biochar produced from manures or biosolids can meet a significant portion of crop P demand.

Nitrogen is useful for soil fertility management. Total nitrogen is the sum of organic nitrogen, ammonia, and nitrate. Even when raw biochar is applied at very high rates, it will not provide sufficient nitrogen for optimal plant growth. Biochar is extremely effective at retaining nitrogen in soil and making it more available for plant uptake over time, which can increase the nitrogen-use efficiency of applied fertilizers. If biochar is applied as a co-composted or nutrient-charged product, it can supplement other forms of nitrogen to meet crop demand. Pelletized and prilled biochar-enhanced fertilizers can contribute to crop nitrogen needs and improve fertilizer efficiency.

Proximal vs. IBI Analysis

Table 4. Proximal Analysis Overlap with IBI

Bulk Density	Organic Carbon	H:C	Total Ash	Total Nitrogen	Carbonates	Butane Activity	Surface Area	Volatile Matter

Source: BOS-Commercial Report version.xlsx

The lab protocols for biochar characteristics are identical for the Proximal and IBI analyses.[5] So, the question that must be answered by the biochar producer or user is whether the broader panel of data is needed for the intended use.

[5] Per Control Labs Testing Lab Manager

The cost difference is significant with the Proximal at about 20% of the cost of the full panel. The biggest difference is that none of the elementals are included in the proximal analysis, however if experience and previous testing indicate this is unnecessary, then the less expensive testing makes sense. The one notable difference in the two choices, which is of particular interest for ag applications, is pH—which is not included in the proximal analysis. This is a simple test which can be performed by the producer or user for a few cents, so should not be a big factor in the decision.

This project explored the two choices by having both series run on select samples, however, the proximal samples were aggregated from a number of BOS runs, so there is no direct comparison which can be cited. The spreadsheet, however, illustrates the relative suitability of the proximal analysis for a given application versus the higher cost of the full IBI panel. From this data set, it seems safe to use the proximal analysis for ag applications as long as the biochar was made using the same technology, with similar locally available woody feedstocks for which there's a full IBI data set for comparison. This assumes there were no amendments or contaminants (like treated lumber or painted items).

Summary

The objective of this report is to compare biochars made with different technologies, specifically Commercial to Biochar made On Site (BOS). Since data from past projects was available, as well as some from collaborating partners, we compiled it into a single spreadsheet to strengthen our conclusions: there is more variability in the BOS scale characteristics than with the Commercial—and the Pilot scale biochars are highly variable by design—but the BOS scale biochars are an acceptable soil amendment, with characteristics comparable to Commercially produced biochars intended for the same purpose.

In practice, specifying biochar with a narrow range of characteristics is challenging for commercial processors. While the field is being constantly influenced by research using different feedstocks, process conditions, and different additives, some characteristics can be controlled more effectively than others—carbon content via processing temperature for instance—and some by post processing, like particle size distribution and nutrient or pH levels.

Most of the elemental characteristics are dependent on the feedstock and processing parameters and are relatively stable once the operating system is optimized and stable.

Commercial biochar production is generally done at a specific temperature for specifically available feedstocks in order to produce a consistent product. Custom biochars are most commonly produced for research at a bench or pilot scale where critical parameters can be more easily controlled; however, as the technology develops, biochars with specific characteristics are more commonly available commercially.

It's apparent, given the large number of characteristics (i.e., product variables) how challenging it is to produce a tightly specified biochar, especially when considering the variability of potential organic feedstocks. There has been significant research done to enhance and refine biochar's specific characteristics and that research is ongoing; the IBI is a good source for an overview of current publications.[6]

Adding rock dusts to the hot char or quenching with compost tea and/or manure-rich liquid are two examples of practical techniques for BOS scale technologies to change the raw biochar characteristics; links to specific examples and more resources are included in the Resources below.

As noted, the characteristics presented in an analysis are defined by Standards currently recommended by the International Biochar Initiative (available at the IBI website), and embodied formally in the European Biochar Standards. While currently voluntary, the IBI standard is used by many other national biochar initiatives, including the US Biochar Initiative which, in turn, is considered "official" by the US Department of Agriculture's various biochar-soil health programs.

The Bottom Line

Based on the data set compiled for this comparison, in general, BOS biochars are comparable to Commercial biochars for in-soil applications. And a Proximal analysis may well suffice as opposed to needing a full IBI panel analysis. What's critical is to match the biochar with the target soil, and is mentioned in almost every biochar publication. That requires an analysis for both and, typically, advice from a soils expert. Most State Extension services offer soil testing, and there are labs who do more extensive soil analysis throughout the US if that level of information and advice is needed, i.e. for commercial crops.

[6] IBI Publications - International Biochar Initiative; additionally, membership in IBI includes a monthly run down of current biochar research publications.

Biochars can be enhanced with treatments during pyrolysis and in post-quenching operations at any scale. The most common is to inoculate the biochars by mixing with compost or manures, or dousing the char with a “tea”. The tea can be simply made with compost or with a more complex solution of rock dusts or chemicals to address specific crop/soil needs. Another common post processing treatment is sizing the biochars to suit an application. Crushing and screening will produce biochars suitable for specific applications. Specifying particle size distribution is common for commercial biochars, however, with BOS additional equipment or physical effort is required. There are some resources suggested in the Appendix which address various treatments.

A final note about commercial vs. BOS: Commercial production lends itself to higher efficiencies and yields. This is mostly due to capturing the heat from the pyrolysis process and by producing by-products (i.e., wood vinegar, bio oil, and syn gas). The major advantage of Biochar made On Site is that there is no transportation cost for moving feedstock; it’s a human scale process, so muscle power is the primary energy source with the heat being lost as a tradeoff for the reduction in volume of the typically brushy feedstocks and converting them into a value added product.

References

Australia New Zealand Biochar Industry Group Farmer's Guide: Farmer's Guide | ANZBIG

Biochar Atlas; http://www.pnwbiochar.org/

Biochar Today; Biochar Today – The latest industry news and scientific research from the field of Biochar

BOS Discussion List: https://biocharonsite.org

Dovetail Partners' library: Dovetail Partners

IBI: Homepage - International Biochar Initiative

Ithaca Institute: Ithaka Institute - Home

Papers by Dr. Stephen Joseph: Stephen Joseph - University of NSW

Wilson Biochar: wilsonbiochar.com

Including a review of Kelpie Wilson's book on biochar making: The Biochar Handbook by Kelpie Wilson: A Review – Biochar Today .

USBI: Home | US Biochar Initiative

Additional Project Related Information:

Biochar Analysis Full Results Spreadsheet (BOS-Commercial Report version.xlsx)

Biochar's Impact on Soil Health StoryMap

Scan QR Code to Visit StoryMap

The work upon which this project is based was funded in whole or in part through a grant awarded by USDA Forest Service (Wood Innovations Project 23-DG-11094200-453). This institution is an equal opportunity provider.