Impact of High Rates of Biochar on the Composting Process and Resulting Products

Nathan Stacey[1], Douglas Collins [1,2], Andy Bary[3], Elizabeth A. Mhyre[4], Steven Seefeldt[4]

[1]Center for Sustaining Agriculture and Natural Resources, Washington State University
[2]Washington State University Extension, Washington State University
[3]Puyallup Research and Extension Center, Washington State University
[4]Mt. Vernon Northwest Research and Extension Center, Washington State University

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Abstract

Composting is an aerobic process driven by complex biochemical reactions that decompose organic matter. The process transforms organic wastes into a valuable downstream product that can be used in agriculture or other settings. Composts are generated from different organic materials and recently, biochar has received much attention as a potential compost feedstock. Biochar is the solid by-product of thermochemical conversion and results when biomass is heated at high temperatures in oxygen starved environments. Because of its unique physical and chemical properties (e.g., high carbon and porosity), biochar can impact the composting process. To better understand biochar's impact on the composting process, we carried out a replicated composting trial. We evaluated two rates of biochar incorporation, at 20 and 40% concentration (volume/volume (v/v)), in a chicken manure and wood chip compost and compared it with an unamended control compost. To investigate the agronomic benefits of this strategy, at the end of the trial the compost products were utilized as a soil amendment in potato production. Biochar incorporation at 20 and 40% (v/v) impacted compost nutrient status, moisture content and temperature profiles, but only minimally so. The linear increase in biochar rate did not result in consistent and significant observations in the response variables we measured. Potential reductions in nitrogen (N) loss were observed in the 40% biochar amended composts, but this likely reflects the additional biochar N, not significant reductions in N loss. In addition, this N retention did not result in drastic differences in potato soil and plant biomass, except in comparisons with the unamended control. Those looking to incorporate biochar as a compost feedstock need to carefully consider the biochar feedstock and production type, and match these properties with appropriate expectations.

Introduction

Composting is an aerobic process that transforms organic waste via decomposition into stabilized organic matter, which then can be used as a nutrient source and conditioner in the soil environment. Decomposition is an abiotic (non-biological) and biotic (biological) process. It is largely governed by biochemical functions of the biotic components (e.g., microbial populations), and so optimal levels of oxygen, moisture, and porosity are critical to its function (Sharma et al., 1997; Steger et al., 2005; Ruggieri et al., 2009). Generally, the composting process moves through three recognized stages: the mesophilic stage (beginning), the thermophilic stage (middle) and the maturation stage (end) (Onwosi et al., 2017). Each stage is characterized by changes in temperature, microbial populations, and physicochemical properties (e.g., plant available nitrogen (N) species) (Barthod et al., 2018). Much research has focused on understanding the complex chemical and physical changes that occur within each stage, so that the composting process can be optimized to create a suitable product for downstream agricultural use (Nafez et al., 2015; Oviedo-Ocaña et al., 2019). For example, it is well understood that the properties of the starting materials (e.g., carbon (C) to nitrogen (N) ratios of feedstocks) influence transformations during composting and thus, impact the properties of the compost end-product.

Biochar is the solid, carbon rich by-product that results from the thermochemical conversion of biomass at elevated temperatures (~300 – 800 °C or 570 – 1470 °F) in environments starved of oxygen (pyrolysis). The physical and chemical properties of biochar are unique: it has a porous structure, a large surface area, and a high concentration of relatively stable C (Aller, 2016). The former two properties make it an appealing product for use in industrial and agricultural contexts because it readily ad- and absorbs chemical compounds (Zheng et al., 2013; Xiang et al., 2020). The ability of biochar to absorb chemical compounds explains its potential role in carbon sequestration strategies (Smith, 2016). Biochar is not a panacea, however, and difficulties with its use arise from variability in the very same beneficial properties listed above. Different feedstocks (e.g., hardwood vs. herbaceous biomass) and production temperatures alter the physical and chemical characteristics of the biochar in functionally important ways (Wang et al., 2015; Tomczyk et al., 2020). High temperature biochars, for example, are less hydrophobic (water repellant) than their low temperature counterparts (Gray et al., 2014). In practice, these differences have a profound effect on the application and performance of the biochar.

Recently, researchers have focused much attention on evaluating biochar as a feedstock in the composting process. Different types of biochar, including those sourced from crop residues, animal manures (e.g., poultry litter), wood, and bamboo have been tested at different incorporation times (i.e., beginning vs. end of composting) and rates (Zhang et al., 2016; Vandecasteele et al., 2016; Agyarko-Mintah et al., 2017; Liu et al., 2017b). Each of these factors (i.e., biochar type, time of incorporation, and rate), individually or in concert, can influence the composting process, the compost end-product, and the surrounding environment (e.g., gaseous emissions or leachate) (Sanchez-Mondero et al., 2018). Following biochar incorporation, changes in the compost pile are generally described in two ways: physically and chemically. Physical changes in the compost pile, like lower bulk density, result from the physical properties of the biochar (such as porosity) and can impact aeration, moisture levels, and temperature, which can reduce greenhouse gas emissions and odors, and accelerate the decomposition process (Xiao et al., 2017). Chemical changes (including reductions in metal bioavailability and N losses) result in part from the large surface area and the unique chemical structure of biochar (Agyarko-Mintah et al., 2017; Liu et al., 2017a). When taken together, the physical and chemical changes that result from biochar incorporation are often described as compost quality improvements, though it should be made clear that these changes and potential improvements are neither uniform nor ubiquitous.

Therefore, to better inform recommendations for those interested in co-composting biochar, we designed two experiments:

1. A compost experiment, which includes compost preparation and mixing, sampling, and a maturity bioassay, to evaluate the use of biochar in the composting process.
2. A field experiment to assess those co-compost products as soil amendments in potato production.

We utilized a regionally produced biochar made from forestry residuals, similar to what a local compost operator might purchase. Moderate rates for biochar incorporation are near 20% (v/v) (~10% weight/weight (w/w), depending on the product), and some have suggested that at high rates (40% (v/v)(≥ 20% w/w, depending on the product)) biochar incorporation will inhibit the composting process. We tested three composts, including an unamended control compost and two different biochar incorporation rates (20 and 40% (v/v)), to better understand the effects biochar has on composting (i.e., at a moderate rate, 20%), to test the upper limits of this compost strategy (i.e., high rate, 40%), and to evaluate the downstream agronomic benefits of these products.

Methods and Materials

Compost experiment

Feedstock materials: Biochar for this project was produced from forestry residuals (Douglas fir (*Pseudotsuga menziesii)* and pine (*Pinus spp*.)) which are heated in two biomass boilers in an oxygen limited portion of the furnace at 871° C. The biochar was purchased from Oregon Biochar Solutions (White City, OR) and select physical and chemical properties are listed in Table 1.

Table 1. Select physical and chemical properties for the forestry residual biochar product.

	Total C (%)*	Total N (%)	C:N	Ash (%)	Volatile Matter (%)	H:C***	Surface Area ($m^2\ g^{-1}$)
Biochar**	78.39	0.44	177.32	3.7	10.1	0.25	533.2

*Percent values (total C and N, ash, and volatile matter) are determined on a dry weight basis.

**Particle size ranged from 1-4 mm (93.7%).

***Hydrogen to Carbon ratio.

To create the biochar amended co-composts, we first developed a base compost mixture which was made from locally procured chicken manure and wood shaving feedstocks. Select physical and chemical properties for the two feedstocks are listed in Table 2.

Table 2. Select physical and chemical properties for the chicken manure and wood shavings feedstocks.

Feedstock	Bulk Density ($g\ cm^{-3}$)	Moisture (%)*	Total C (%)	Total N (%)	C:N	pH	EC ($dS\ m^{-1}$)
Chicken Manure	0.87	26	24.02	2.56	9.37	8.0	20.5
Wood Shavings	0.23	66	54.22	0.16	341.38	5.0	0.5

*Percent values (moisture, total C and N) are determined on a dry weight basis.

Compost preparation and mixing

To evaluate the composting process, each of three treatments (control compost, biochar 20%, and biochar 40%) were composted in triplicate in nine, 1.43 m^3 vessels, simultaneously, for 34 days.

Because composting is an aerobic process moderated by microbial organisms, it is critical that the physical, chemical, and environmental conditions of the compost blend are optimized. Prior to the composting trial, we mixed different ratios of wood shavings to chicken manure (3:1, 4:1, and 5:1 (v/v)) and evaluated properties including C:N and percent free airspace. C:N ratios and percent free airspace are good indicators that the compost blend has the proper quantity of nutrients for the microbial population and is porous enough to allow for oxygen exchange. The ratio of 4:1 wood shavings to chicken manure (v/v), resulted in a C:N ratio of 25:1 and 34.6 percent free air space. This was optimal for our composting experiment, and so we selected this blend as our base mix which was also utilized as the control treatment in the composting experiment.

To prepare the base mix, 3407 kgs (wet wt.) of chicken manure and 3744 kgs (wet wt.) of wood shavings were scooped and loaded into a large manure spreader that homogenized the mix and created one large pile from where the nine reactors were filled. Utilizing this base material, the mixing process (manure spreader) was duplicated for the other two treatments (biochar 20 and 40%) save for the differences in material volume which were blended at the appropriate rates.

One replication of the experiment (i.e., three vessels filled with each of three treatments) was prepared per day; the process was as follows:

1. Perforated PVC pipes were installed on the floor of the vessel, perforations oriented down (this allowed us to aerify the material later),
2. Wood chips (17.7 kgs, wet wt.) were spread evenly over the PVC pipes and covered with mesh screen (plenum),
3. Compost material was added until it reached 101 cm (from the bottom) with brief pauses at 40 and 81 cm so that temperature sensors could be installed,
4. The material was capped with additional wood chips (40.82 kgs, wet wt.) (top cap) and covered with a non-permeable lid.

In addition, samples and weight of the compost components (i.e., compost, plenum, and top cap) were collected during the vessel preparation and saved for later analysis.

Composting and sampling

Once the compost vessels were filled on day 1 (pre), composting proceeded outdoors until composting temperatures were stable, which occurred at 34 days. Vessels were continually supplemented with forced air from ½ horsepower electric blowers every 60 minutes for 20 seconds and probes were set to collect temperature data every 15 minutes for the duration of the study.

At day 13 (mid) and for each of the replications, composting components (top cap, compost, and plenum) were removed and mixed, evaluated for moisture and bulk density, and if needed, supplemented with additional water to meet 65% moisture content. The vessels were re-packed and allowed to compost for an additional 21 days.

At day 34 (end) and for each of the replications, the composting vessels were carefully disassembled so that the composting components (top cap, compost, and plenum) could be removed, placed on separate tarps, weighed and sampled. The compost samples, including those from the beginning of the experiment (pre-samples) were later analyzed for percent moisture, electroconductivity (EC), pH, total C and N, and NH_4-N, and NO_3-N. Analysis for composts followed the methods listed in the Test Methods for the Examination of Composting and Compost (TMECC), the standard set of laboratory protocols for the composting industry.

The nutrient content of compost is one element that helps define its economic and agronomic value. To assess whether these rates of biochar incorporation influenced nutrient cycling, and thus nutrient content, we utilized data from pre- and post-composting samples (including top cap, compost, and plenum) to calculate nutrient loss or gain via a mass balance approach. Gains or losses were calculated using the following equation:

$$\left[\frac{Beginning\left(dry\ material\ (kg\ )\times\ concentration\ (mg\ kg^{-1})\right)-End\left(dry\ material\ (kg\ )\times\ concentration\ (mg\ kg^{-1})\right)}{Beginning\left(dry\ material\ (kg)\times\ concentration\ (mg\ kg^{-1})\right)}\right]$$

The resulting value was multiplied by 100 to get percent loss.

Compost maturity bioassay

Compost maturity is typically defined by stable organic matter (i.e., no large fluxes of CO_2) and a lack of phytotoxic compounds and plant and animal pathogens. There are many ways to evaluate compost maturity, but here we used a cucumber seedling growth and emergence test.

Compost material (300 cm^3) from each of the three treatments (control, biochar 20%, biochar 40%) was blended with pre-soaked vermiculite (300 cm^3) and scooped into three rows of a 9-cell plastic tray. Two additional rows were filled with soilless potting media and vermiculite, which acted as the positive and negative control, respectively. Into each individual cell, two cucumber seeds were sown, covered with one cm of material, and this entire process was repeated two additional times (3 replications, 72 total seedlings). Plastic tray flats were placed into plastic bags to prevent moisture loss and then set on benches in a greenhouse for 14 days. To calculate percent emergence, the number of fully emerged seedlings were counted for each treatment, divided by the number of total emerged seedlings for the positive control, and then multiplied by 100. To find percent vigor, we first calculated the average height of growth for the positive control; this became the benchmark for vigor comparisons. We then tallied the number of seedlings at or above this height, divided the treatment totals by positive control totals, and multiplied by 100 to get percent.

Potato field experiment

Potato plots were established at the Washington State University Mt. Vernon Research and Extension Center in Mt. Vernon, WA. Prior to amendment, research plots were fertilized with phosphate (11-52-0, 163 kg ha^{-1}), langbeinite (0-0-22, 172.6 kg ha^{-1}), muriate of potash (0-0-62, 168.1 kg ha^{-1}), ammonium sulfate (20-0-0, 103.1 kg ha^{-1}), and urea (46-0-0, 196.1 kg ha^{-1}).

Then, in a randomized complete block design, replicated four times, we amended soils (15 June 2020) with seven treatments: an unamended control, a control compost at high and low rates, biochar 20% compost at high and low rates, and biochar 40% compost at high and low rates. Treatments were applied by hand to meet target rates of 15 and 7 Mg dry C ha^{-1} (high and low, respectively). Actual rates are listed in Table 3.

Table 3. Amendment rates for the potato field trial.

	Control Compost		Biochar 20%		Biochar 40%	
Rate	High	Low	High	Low	High	Low
Wet Weight (t ha^{-1})*	51.34	24.05	44.02	25.85	43.06	20.07

*Wet weight is US tons.

Following amendment, plots were tilled to 15 cm, planted with cut potato (*Solanum turberosum* L. var. *Chieftain*) (18 June 2020), and later hilled 21 days later (9 July 2020). One hundred and thirty-two days later (28 October 2020), from the center row of each treatment, three plants were harvested for above- and below-ground biomass. Leaves were collected, dried at 43° C, and weighed, and tubers from the same three plants were collected, counted, and later weighed.

To evaluate the amendment effect on potato soils, two bulk density cores taken to a depth of 15 cm (136.4 cm^3 each) were collected and stored, and an additional 10-12 soil cores (11.4 cm^3 each) were collected, homogenized, and later dried at 26° C with forced air. Soils were analyzed for total C and N, NH_4-N, and NO_3-N, and soil bulk density was assessed using dried subsamples, calculated as the weight of dried soil (g) divided by soil volume (cm^3). Total C and N concentrations were assessed by dry combustion (LECO Tru-Spec CN analyzer (Leco Crop., St. Joseph, MI)), and following 1 N KCL extractions, NH_4-N was determined by colorimetric analysis (LACHAT flow-injection analyzer (Hach Company, Loveland, CO)) and NO_3-N by spectrophotometric analysis following cadmium reduction (Gavlak et al., 2005).

Statistical analysis

Treatment difference for the various composting (e.g., bulk density and moisture) and field experiments (e.g., total N) were tested using analysis of variance (ANOVA) which included the effects of treatment and replication. In the bulk density and moisture analysis, time periods were treated separately and when appropriate, means were separated using Tukey's HSD ($P<0.05$).

Results and Discussion

Compost physical parameters (bulk density, moisture content, and temperature)

Following biochar incorporation and in comparisons with the control, obvious and inverse trends were observed in mean values for wet bulk density and moisture content: as biochar incorporation rates increased, bulk density values decreased and moisture content improved (Table 4). Changes in bulk density and moisture content mean values, however, were small, and significant differences were only observed in bulk density pre-samples and moisture content end-samples (Table 4).

Similar results for bulk density have been reported at different scales (lab scale compost reactors) (Ravindran et al., 2019). The results reported here likely reflect the physical properties of the biochar, such as its high surface area and porosity. The inherently low bulk density of the biochar likely diluted the original material, which caused a reduction in bulk density, and this effect was diminished over time as the volume of the compost shrunk (i.e., chemical transformations in the compost process are responsible for changes in compost volume). Less clear is the exact mechanism by which the percent moisture is affected. It may be that pores in the biochar are filled with water, or it could be that water is held tightly between the surface of the biochar and other materials in the compost. Likely, the effect is a combination of the two.

Table 4. Mean values in each of three treatments, control, biochar 20% (B20), and biochar 40% (B40) for compost bulk density and moisture content at three different times (Pre, Mid, and End).

	Pre			Mid			End		
Property	Control	B20	B40	Control	B20	B40	Control	B20	B40
Bulk density*	0.581a***	0.533b	0.476c	0.460	0.423	0.414	0.500	0.462	0.443
Moisture** content	58.6	62.0	64.0	57.3	59	61.7	57.3a	60.3ab	63.0b

*Bulk density values are reported in Mg m^{-3}.

**Moisture content is percent.

***Mean values within a collection period (Pre, Mid, and End) and variable row (Bulk density or Moisture content) followed by different letters are significantly different according to Tukey's HSD test ($P<0.05$).

In composting, temperature is typically used to evaluate the status of the process because it is tied to the degradation of phytotoxic compounds and pathogens (among other processes); to do so composts must reach 55 °C for at least three days. Compost temperature profiles are described by three different stages: mesophilic (beginning), thermophilic (middle), and maturation (end) and the length of time of each can vary according to many different variables (Onwosi et al., 2017).

All composts in this study reach a minimum of 55 °C for three days (Figure 1). We evaluated temperatures at two levels within the compost (shallow and deep, 80 and 41cm from the base, respectively), but depth did not reveal major differences in temperature trends, as trends in the two were nearly identical (Figure 1). Temperatures in the biochar amended composts increased at a greater rate (i.e., reached thermophilic stage more quickly) than the control compost until roughly 36 hours after the start of composting and then temperatures in the control piles exceeded those in the biochar treatments and remained elevated for the duration of the trial (Figure 1). Our observations are somewhat similar to what has previously been reported (Mao et al., 2018), except that in our study, we observed considerable heat dissipation (loss) in the two biochar treatments when compared to the control. Temperature increases in biochar amended composts are often attributed to increased microbial activity (i.e., more microbial activity generates more heat), and that may have been true in the initial stages of our study, but that effect was not sustained and clearly declined at ~ 36 hours in biochar treatments. This may be evidence of exhausted nutrient stores (i.e., labile C and N available for microbial growth are spent) but it could also reflect the impact the physical properties of biochar have on aeration and thus, heat exchange. If the differences in temperature profiles among treatments are transferable to larger scales, this may have implications for compost producers considering this strategy. Incorporating biochar at higher rates may require more N (nutrients), proportionally, than what was used here and, if at some unknown high rate of incorporation the heat loss we measured continues, the compost process could be negatively impacted. On the other hand, if the rate of temperature increase was consistent (when incorporating biochar), this may reduce the time required to reach a stable and mature compost product. Differences in scale (i.e., comparisons between laboratory and industrial scale composting), however, can have considerable effect on the physical and chemical properties of a compost and thus, extrapolations from these data should be done with this in mind.

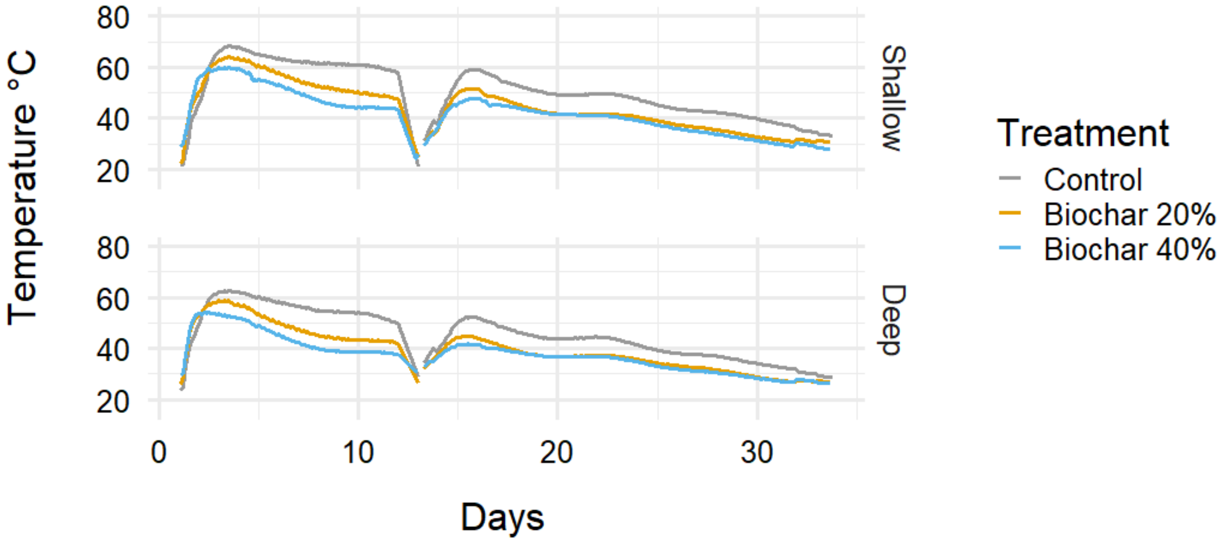

Figure 1. Temperature profiles for each of three treatments over the 34-day composting trial. The break in temperature at day 13 indicates when the compost was turned and each treatment line (colored grey, orange, and blue) represents the average of three replications.

Compost chemical parameters

Table 5 lists mean values for chemical properties evaluated before (Pre) and after (End) composting. Included in the list are electroconductivity (EC) and NO_3-N and NH_4-N. EC is a measure of soluble salt content which can injure plants at high levels. NO_3-N and NH_4-N are forms of plant available N and are immediately available in the soil environment.

In pre-compost samples, the only significant difference we observed was in total C mean values which was identified in comparisons between the control and biochar 40% treatment (Table 5).

In contrast, at the end of composting, significant differences were observed in mean values for total C, C:N, EC, and NO_3-N. Interestingly, further comparisons among biochar treatments did not reveal consistent rate differences: total C and EC differences were observed between the control and the biochar treatments equally, while C:N and NO_3-N differences were measured between the control and B40 treatment.

Table 5. Mean values for chemical properties in each of three treatments, control (C), biochar 20% (B20), and biochar 40% (B40) at two collection times, before (Pre) and at the end (End) of composting.

	Pre			End		
Property	C	B20	B40	C	B20	B40
Total C (%)*	35.9a**	39.4ab	45.6b	30.2c	38.0d	42.3d
Total N (%)	1.56	1.56	1.54	1.13	1.17	1.22
C:N	23.0	25.6	29.3	26.8a	32.6ab	34.8b
pH	8.1	8.8	8.8	7.9	7.9	7.6
EC (dS m^{-1})	10.9	9.29	8.0	7.7a	6.8b	6.6b
NO_3-N (mg kg^{-1})	9.0	8.3	9.0	1328a	1524a	1955b
NH_4-N (mg kg^{-1})	6014	4848	4674	268	29	41

*Percent total C and N are reported on a dry weight basis.

**Mean values within a collection period (Pre and End) and variable row (e.g., Total C) followed by different letters are significantly different according to Tukey's HSD test ($P<0.05$).

Concentrations of C and N, including total and inorganic forms of N, illustrate well understood chemical behavior and transformations (Wei et al., 2014; Kammann et al., 2015; Hagemann et al., 2018). The significant differences observed in total C in pre compost samples reflect the additional C that was added as biochar, and the non-significant trends, like those in C:N ratios and NH_4-N mean values, are indicative of the differences in feedstock proportions (i.e., NH_4-N concentrations, known to be elevated in chicken manure, were diluted by increasing rates of biochar).

Following composting, mean values for total C, while expected, could reflect additional processes other than initial feedstock volumes. In comparisons with the control, the significantly elevated levels of total C may illustrate the persistent qualities of biochar C (i.e., it is more resistant to degradation). Additionally, these increases may reflect biochar's ability to ad- and absorb soluble compounds like dissolved organic C (DOC), which could alter C cycling and the resulting losses of CO_2. Similarly related, the increases in NO_3-N, at the highest rates of biochar incorporation and in comparisons with the control likely reflect similar processes of ad- and absorption. This effect has been widely studied in biochar co-composts (Hagemann et al., 2017). Interestingly, the decline in EC values is somewhat unexpected as EC is a measure of soluble salts, which includes the NO_3-N anion. In the biochar 40% treatment, we observed high levels of NO_3-N, however, the concentration of NO_3-N does not indicate the solubility of the anion and may not impact EC. In addition, researchers have shown that quantifying available NO_3-N in biochar amended composts can be tricky (Hagemann et al., 2017).

Preliminary data from nutrient content analysis suggests that biochar incorporation does reduce N loss, but only at the highest rate and in comparisons with the control (Figure 2). The reduction, if representative, is still small, 5.5-.5.7% (Figure 2) and may reflect the difference in starting N quantities rather than reductions in N loss.

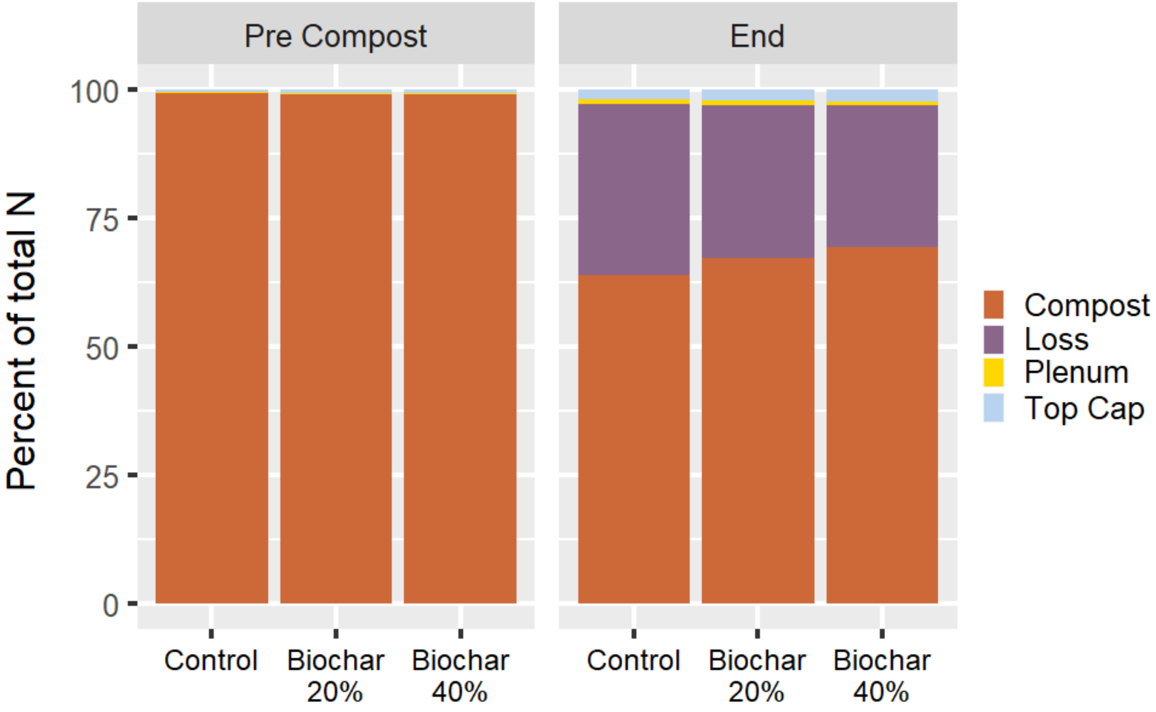

Figure 2. Percent of total N in each of three treatments and three composting components (Top Cap, Compost, and Plenum) illustrating the difference between beginning (Pre Compost) and end (End) composting. Included in the graph is percent N loss (purple color, Loss) that demonstrates the percent loss of N for each treatment.

Reductions in nitrogen loss following biochar co-composting are commonly reported (Khan et al., 2014; Malinska et al., 2014). However, the N pathway where that reduction occurs (i.e., gaseous NH_3^+ or soluble NO_3-N) and the magnitude of that effect varies widely. As with many biochar co-compost experiments, the size, feedstock, and production temperature of the biochar influences these observed effects, but with N, additional characteristics, like those of the compost feedstock (such as inorganic N) also determine the manner and quantity of N responses observed.

Compost maturity bioassay

In comparisons with the positive control, there were no statistical differences in percent emergence and seedling vigor for any of the comparisons made between treatments. According to the cucumber bioassay, all our composts reached maturity (Table 6).

Table 6. Percent emergence and seedling vigor for each of three treatments following composting, including the positive control comparison.

	Positive Control	Control	Biochar 20%	Biochar 40%
Emergence (%)	100	98.4	95.1	94.7
Seedling Vigor (%)	100	104	121	102

Potato field trial

The potato field trial was conducted over one growing season and therefore extrapolation from this limited data set should be conducted with caution.

Following amendment and in comparisons with the unamended control, soil bulk density and total N mean values were significantly affected by amendment, but only in comparisons with the ConComp (control compost) and B40 high rates, respectively (Table 7). Bulk density values decreased while total N concentrations increased; all other variables were unaffected by the various compost products at low and high rates (Table 7).

Table 7. Soil physical and chemical properties following compost amendments at low and high rates and one growing season.

	Control*	ConComp		B20		B40	
Property		Low	High	Low	High	Low	High
BD**	1.91a***	1.83ab	1.79b	1.86ab	1.84ab	1.85ab	1.82ab
Total C† (%)	1.07	1.13	1.45	1.17	1.26	1.28	1.23
Total N (%)	0.137a	0.145ab	0.169ab	0.156ab	0.168ab	0.163ab	0.174b
NO3-N (mg kg^{-1})	230	246	273	300	312	376	369
NH4-N (mg kg^{-1})	19.2	16.5	21.8	22.5	19.6	17.9	19.6

*Field amendments are as follows: Control is the unamended control, ConComp is the control compost at low and high rates; B20 is the biochar amended compost 20% at low and high rates; B40 is the biochar amended compost 40% at low and high rates.

**BD is Bulk density and is reported in Mg m-3.

***Means within a variable row (e.g., BD) followed by different letters are significantly different according to Tukey's HSD test (P<0.05).

†Total C and N values are reported as dry weight.

Soil bulk density, like bulk density in compost, can be altered by the rate and physical properties of an amendment material. The ConComp material was amended at the highest rate of application in our field experiment (Table 3) and so, the decrease in soil bulk density is expected.

It is interesting, however, that no other material decreased soil bulk density. In potato production, the soil is initially tilled, planted, and re-disturbed by creating soil hills over the potato plant. This second soil disruption may account for the unchanged soil bulk density.

Soil total N represents organic and inorganic forms of soil N. Though a clear trend was obvious in soil NO_3-N values (i.e., increasing NO_3-N values following the increase of biochar incorporation and amendment rates), in comparisons between treatment, no differences were detected. This means that the significant increase in total N we reported (B40 high treatment > control) is likely an increase in organic N. Our research plots were amended with supplemental N, in the form of synthetic fertilizer, which effectively removes N limitations that may restrict soil microbial growth and reproduction. The observed increase in total N, and thus organic N, may reflect an increase in soil microbial activity (i.e., the organic N increase represents an increase in microbial cells), but because we did not evaluate microbial properties, it is unknown whether those populations were affected by the B40 high treatment.

Comparable results were observed in collections of potato plant biomass as tuber weight significantly increased in plots amended with the B40 high treatment, but this was observed only in comparisons with the control (Table 8). Conversely, following amendment, observations on leaf weight and tuber number revealed no significant difference in comparisons between treatments (Table 8).

Table 8. Mean values for potato plant biomass including leaves and tubers, following amendment and one growing season.

	Control*	**ConComp**		**B20**		**B40**	
Potato biomass		Low	High	Low	High	Low	High
Leaves (kg ha-^{1})	77.3**	84.2	100	97.1	94.4	92.4	118
Tuber weight (kg ha^{-1})	1.49a	1.70ab	1.89ab	1.87ab	1.77ab	1.67ab	2.11b
Tuber number (ha^{-1})	10599	10458	10741	9751	10034	10317	12295

*Field amendments are as follows: Control is the unamended control, ConComp is the control compost at low and high rates; B20 is the biochar amended compost 20% at low and high rates; B40 is the biochar amended compost 40% at low and high rates.

**Means within a variable row (e.g., leaves) followed by different letters are significantly different according to Tukey's HSD test ($P<0.05$).

In potato production, composts are typically used as soil conditioners, not as the primary plant nutrient source. Therefore, the limited responses we observed in potato soil and plant biomass following compost amendment are not unexpected. Additionally, the fertilizer application made prior to compost amendment likely masked potential soil and plant responses; this is a known effect and has been reported elsewhere (Wilson et al., 2019). Because compost products supply N at much slower rates than a synthetic fertilizer, a second season of growth would likely reveal treatment differences.

Conclusions

We incorporated high temperature, woody waste biochar into chicken manure and wood chip compost at two rates, moderate (20% v/v) and high (40% v/v), to evaluate the impacts of biochar on the composting process. Included in the experiment was a control produced from the same feedstocks, chicken manure and wood chips, but with no biochar. Compost physical and chemical responses were collected over a 34 day period and then evaluated between the three compost products. The same three composts were then evalutated in potato production at low and high rates which also included an unamended control. Following one growing season, yield and soil responses were collected and compared.

For the composting experiment:

- All composts reached 55 °C for a minimum of three days which meets the compost industry standard for pathogen reduction.
- Composts with 20% biochar (v/v) incorporation rarely statistically impacted the variables we measured.
- Composts with 40% biochar (v/v) incorporation:
    1. reached 55 °C nine hours faster than the control, but also lost heat at a greater rate.
    2. had 6% greater moisture content in comparisons with the control.
    3. had the highest concentrations of NO_3-N, indicating greater rates of nitrification, effectively stabilizing more volatile ammonium in the compost pile
    4. reduced N loss

For the field experiment:

- The control compost, amended at the highest rate, reduced soil bulk density and increased soil total N.
- Potato tuber yield was increased, but only in comparisons between the control and the high rate of compost with 40% biochar.

In summary, biochar incorporation, in 1.43 m^3 composting vessels, did impact the composting process in terms of both physical and chemical responses, but not negatively so. The greatest impacts were measured when biochar was incorporated into the chicken manure and wood chip compost at the highest rates, 40% (v/v). When the composts were evaluated in potato production, composts with 40% biochar amended at the high rate increased tuber yield in comparisons with the control. Soil and yield data, however, were collected from one growing season and must be carefully interpreted. Compost producers considering this type of compost strategy need to carefully evaluate the feedstock and production process for a chosen biochar so that their expectations align with the most likely outcomes. Similarly, future work should also carefully consider the biochar feedstock and production temperature with additional experiments that evaluate the potential for greater compost N loss reductions. Multiple year field trials that utilize a co-composted biochar would also help elucidate the longevity and performance of N that may become slowly available in soils following biochar co-compost amendment.

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