Chemical Properties of Biochar Materials Manufactured from Agricultural Products Common to the Southeast United States

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SUMMARY. **The use of biochar as a soil amendment has fostered much attention in recent years due to its potential of improving the chemical, physical, and biological properties of agricultural soils and/or soilless substrates. The objective of this study was to evaluate the chemical properties of feedstocks, common in the southeast United States, and their resulting biochar products (after being torrefied) and determine if the chemical properties were within suitable ranges for growers to use the biochar products as root substrate components. Poultry litter biochar produced at 400 °C for 2 hours had a higher total phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), sodium (Na), and zinc (Zn) concentration than biochar made using the same process with mixed hard wood species, miscanthus (*Miscanthus capensis*), cotton (*Gossypium hirsutum*) gin trash, switchgrass (*Panicum virgatum*), rice (*Oryza sativa*) hull, and pine (*Pinus* sp.) shavings feedstocks. The pH of the biochar products ranged from 4.6 for pine shaving biochar to 9.3 for miscanthus biochar. The electrical conductivity (EC) ranged from 0.1 dS·m^{-1} for mixed hardwood biochar to 30.3 dS·m^{-1} for poultry litter biochar. The cation exchange capacity (CEC) of the biochar products ranged from a low of 0.09 meq/g for mixed hardwood biochar to a high of 19.0 meq/g for poultry litter biochar. The water-extractable nitrate, P, K, Ca, Mg, sulfate, boron, Cl, Cu, Fe, Mo, Na, and Zn were higher in poultry litter biochar than in all of the other types of biochar. The high EC and mineral element concentration of the poultry litter biochar would prevent its use in root substrates except in very small amounts. In addition, the high degree of variability in chemical properties among all of the biochar products would require users to know the specific properties of any biochar product they used in a soil or soilless substrate. Modifications to traditional limestone additions and fertility programs may also need to be tested and monitored to compensate for the biochar pH and mineral nutrient availability. Users should be aware that biochar products made from different feedstocks can have very different chemical properties even if the same process was used to manufacture them.**

Biochar is a term that refers to a black carbon-rich material that is produced from organic matter at temperatures lower than 700 °C in an oxygen-limited atmosphere (Lehmann and Joseph, 2009) and is generally considered to be similar to charcoal. There are different processes used to make biochar, including pyrolysis, gasification, and torrefaction, and these processes may differ in temperature, residency time, and oxygen availability. Although different processes have their advantages and disadvantages, researchers worldwide are working on optimizing and evaluating biomass conversion processes to improve quality and performance of biomass-based production of fuels, chemicals, and biochar. Specific and unique properties of each biochar product depended on the properties of the original feedstock material (Altland, 2014) and method of production employed (Spokas et al., 2012). It has been reported that the higher the temperature, the smaller and more porous the resulting biochar particles became (Kloss et al., 2012). These smaller particles tended to have proportionally more surface area (Shackley et al., 2013) which had benefits such as an increased CEC.

Due to its high carbon concentration, biochar has the potential to be used in a number of applications including soil conditioning, as activated carbon or in chemical manufacturing. The application of biochar to soils contributed to the sequestration of carbon from the atmosphere, since carbon captured from the environment by the biomass was shown to be retained in the soil (Manya, 2012). Wood contained around 50% carbon that increased to 70% to 80% once it was processed to biochar. This carbon could be stored from the atmosphere when applied to the soil (Winsley, 2007). In addition, the utilization of biochar improved the quality of the soil because of its sorption qualities that helped to retain nutrients and nitrogen (Ippolito et al., 2012).

The components of horticultural substrates used in commercial greenhouse and nursery operations can be a major production cost, as most customary components are commonly shipped from outside the United States or manufactured substrates are transported significant

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
25.4	inch(es)	mm	0.0394
1	meq/g	mol·kg^{-1}	1
1	mmho/cm	dS·m^{-1}	1
28.3495	oz	g	0.0353
28,350	oz	mg	3.5274×10^{-5}
1	ppm	mg·L^{-1}	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

distances from the production facility to the end user. Interest in using biochar for horticultural purposes has increased substantially in recent years due to its potential as a low-cost substrate component. In particular, biochar products have been shown to be a potential replacement for perlite in greenhouse substrates (Northup, 2013), because it is lightweight, porous, and thought to have potential cost-saving benefits over perlite. Other reported benefits of using biochar products in substrates include the potential of increasing CEC (Nemati et al., 2015) and rhizosphere biology (Graber et al., 2010).

Numerous researchers have evaluated the use of biochar and products similar to biochar as substrate components and have reported mixed results. Coal cinders were evaluated as components in substrates to enhance the physical and chemical properties of a pine bark nursery substrate (Neal and Wagner, 1983) and again as a component in the growth of azalea [*Rhododendron obtusum* (Wagner and Neal, 1984)]. Coal cinders were found to contain high concentrations of heavy metals, which limited their use in substrates even though plant growth trials proved to be successful with up to 50% (by volume) cinder incorporation. Regulski (1984) reported the use of a gasifier residue as an amendment in a pine bark substrate to have reduced shrinkage, compared with the pine bark control, and provided increased easily available water and water buffering capacity for the duration of a 9-month crop. Holcomb and Walker (1995) reported the growth of chrysanthemum (*Chrysanthemum indicum*) and poinsettia (*Euphorbia pulcherrima*) in coal gasification slag amended substrates to be equal to plants grown in a peat:perlite control at up to 50% amendment (Bi et al., 2009; Evans et al., 2011). Researchers who conducted a container experiment using natural field soil amended with rice hull biochar demonstrated increased plant growth for lettuce (*Lactuca sativa*) and chinese cabbage (*Brassica chinensis*) when compared with plants grown in unamended soil (Carter et al., 2013). Pepper (*Capsicum annuum*) grown in coconut (*Cocos nucifera*) coir fiber amended with wood-derived biochar was shown to have increased plant growth and yields as compared with those grown in coconut coir fiber alone (Graber et al., 2010). Those authors speculated that the improved plant growth was a result of the biochar stimulating the beneficial plant growth promoting rhizobacteria populations or due to hormesis (positive plant growth response to low doses of phytotoxic or biocidal chemicals) caused by the biochar. Red oak (*Quercus rubra*) biochar added to peat or peat-vermiculite substrates resulted in an increased shoot biomass of hybrid poplar (*Populus* sp.) cuttings as a result of increased nutrient concentrations and availability due to the high CEC and initial nutrient content of the biochar (Headlee et al., 2014). In contrast, Northup (2013) reported that the incorporation of hardwood-produced biochar into the substrate resulted in either no effect or decreased growth of pepper, tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), marigold (*Tagetes patula*), and petunia (*Petunia* ×*atkinsiana*).

There are conflicting reports on the potential for biochar to be used as a soilless substrate component. This could be due to the wide range of biomass materials used to produce biochar, which may alter the properties of the final product. Any biochar products that are to be used in horticultural substrates must have chemical properties within acceptable ranges for such use. Therefore, the objective of this study was to evaluate the chemical properties of feedstocks common to southeast United States and their resulting biochar products and determine if the chemical properties were within suitable ranges for growers to use the biochar products as root substrate components.

Materials and methods

Various agricultural by-products common to the southeast United States were collected and used as feedstocks for the production of biochar products. The feedstocks included rice hulls, hardwood chips composed of a mixture of oak, poplar, and ash (*Fraxinus* sp.), softwood chips from pine shavings, cotton gin trash, switchgrass, miscanthus grass, and poultry litter. The feedstocks were air dried and ground to particle sizes between 10 and 20 mm in diameter using a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ). Feedstocks were then transported to the bioenergy laboratory at the Rice Research and Extension Center, University of Arkansas System Division of Agriculture (Stuttgart, AR).

The biochar was produced in 1-gal cylindrical metal containers filled with feedstock samples and placed in a controllable muffle furnace (model 3-1750; Neytech Vulcan, Bloomfield, CT). Each container was loaded with 400 g of raw feedstock before tightly securing the lid allowing only the evolved volatiles to escape through 3-mm vents on the lid. In this study, the evolved volatiles were not collected nor quantified. Before placing the containers in the furnace, they were purged with nitrogen (N) gas through one of the 3-mm vents for 10 min to ensure minimal oxidation of the feedstock. The furnace temperature and the residence time were set at 400 °C and 2 h, respectively. The feedstocks were placed into the heated furnace once the desired temperature level was achieved. After retrieval from the heated furnace, containers were immediately covered with aluminum foil to prevent biochar oxidation and were allowed to cool.

The original feedstocks and their resulting biochar products were sent to a commercial laboratory for analysis (MMI Laboratories, Athens, GA). Two types of analyses were conducted on the feedstocks and biochar products. The first was a total elemental analysis. The feedstocks and biochar products were dried in an oven at 100 °C, ground and acid digested. The N, P, K, Ca, Mg, S, boron (B), Cu, Fe, Mn, Mo, Na, and Zn concentrations were determined using the filtered extract for simultaneous inductively coupled plasma emission spectrometry (Jones, 1977; Munter and Grande, 1981).

The second test was a deionized water-based saturated media extract using a volume of 1 part feedstock or biochar product and 1.5 part deionized water (Warncke, 1988). The solution was then incubated for 45 min and the solution was extracted using a vacuum. The pH was determined using a pH meter (Accumet model AB 15; Fisher Scientific, Pittsburgh, PA), and the EC was determined using an EC meter (model 441; Corning, Corning, NY). The ammonium (NH_4^+) was determined by the nitroprusside–salicylate procedure (Wall et al., 1975), and the nitrate (NO_3^-) concentration was determined using the copperized cadmium reduction procedure (Keeney and Nelson, 1982). The concentrations of P, K, Ca, Mg, sulfate (SO_4^{2-}), B, Cl, Cu, Fe, Mn, Mo, Na, and Zn were determined using the filtered extract for simultaneous inductively coupled plasma emission spectrometry (Jones, 1977; Munter and Grande, 1981). The CEC of the biochars and original feedstocks were determined according to procedures described by Dumroese et al. (2011) and Kloss et al. (2012).

There were three independent replications (different production runs) per feedstock and biochar product. An analysis of variance was conducted to determine if significant differences occurred among the different feedstocks and biochar products. Where significant differences occurred, a least significant difference mean separation test was conducted to determine significant differences between specific means.

Results

TOTAL ELEMENTAL ANALYSIS. The N concentration of the feedstocks ranged from 0.14% for pine shavings to 2.7% for poultry litter (Table 1). The N concentration of the biochar products ranged from 0.71% for mixed hardwood biochar to 3.57% for the poultry litter biochar. The cotton gin trash biochar had the second highest N concentration at 1.37%. In all cases except for the rice hulls, the N concentration was higher in the resulting biochar products than in the respective feedstock. The N concentration of rice hulls and the resulting rice hull biochar was not different.

The P concentration of the feedstocks ranged from 2.64 $mg \cdot L^{-1}$ for pine shavings and switch grass to 41.7 $mg \cdot L^{-1}$ for mixed hardwoods (Table 1). The P concentration of the biochar products ranged from 4.49 $mg \cdot L^{-1}$ for switchgrass to 125.9 $mg \cdot L^{-1}$ for the mixed hardwoods biochar (Table 1). In all cases except for the switch grass and rice hulls, the P concentration was higher in the resulting biochar product than in their respective feedstocks.

The K concentration of the feedstocks ranged from 784 $mg \cdot L^{-1}$ for pine shavings to 17,740 $mg \cdot L^{-1}$ for poultry litter (Table 1). The K concentration of the biochar products ranged from 1985 $mg \cdot L^{-1}$ for mixed hardwoods to 18,391 $mg \cdot L^{-1}$ for the poultry litter biochar (Table 1). The K concentration was higher in the resulting biochar products than in the respective feedstocks for the mixed hardwoods, miscanthus, and pine shavings. However, the K concentration was lower in the cotton gin trash biochar than in the cotton gin trash feedstock.

The Ca concentration of the feedstocks ranged from 1054 $mg \cdot L^{-1}$ for rice hulls to 15,226 $mg \cdot L^{-1}$ for poultry litter (Table 1). The Ca concentration of the biochar products ranged from 2078 $mg \cdot L^{-1}$ for rice hull biochar to 25,203 $mg \cdot L^{-1}$ for the poultry litter biochar (Table 1). The Mg concentration of the feedstocks ranged from 190 $mg \cdot L^{-1}$ for mixed hardwoods to 4237 $mg \cdot L^{-1}$ for poultry litter (Table 1). The Mg concentration of the biochar products ranged from 340 $mg \cdot L^{-1}$ for rice hull biochar to 4586 $mg \cdot L^{-1}$ for the poultry litter biochar (Table 1). The Ca and Mg concentration was higher in the resulting biochar products than in the respective feedstocks for all of the biochar products except for rice hulls.

The S concentration of the feedstocks ranged from near 0% for pine shavings to 0.37% for poultry litter (Table 1). The S concentration of the biochar products ranged from 0.02% for rice hull and pine shaving biochar to 0.56% for the poultry litter biochar (Table 1). The S concentration of the poultry litter biochar was higher than for the poultry litter feedstock, but there was no difference in the S concentration of the other feedstocks and their respective biochar products.

For all micronutrients except B, the poultry litter feedstock and the poultry litter biochar had higher concentrations of micronutrients than all of the other feedstocks and their respective biochar products (Table 2). The B concentration was higher in cotton gin trash biochar than all other biochar products. The Cu, Fe, and Mo concentration did not differ between the poultry litter feed stock and the resulting poultry litter biochar. However, the poultry litter biochar had higher Mn, Na, and Zn, and lower B than its feedstock. All of the other biochar products except pine shavings had higher concentrations of Fe and Mn than their respective feedstocks. However, the concentration of the other micronutrients varied with no consistent patterns among feedstocks or biochar products or between a feedstock and its resulting biochar.

WATER-EXTRACTABLE CHEMICAL PROPERTIES. The pH of the feedstocks ranged from 4.6 for the pine shavings to 8.7 for the poultry litter (Table 3). Poultry litter was the only feedstock with an alkaline pH. The pH of the biochar products ranged from 4.6 for pine shavings to 9.3 for miscanthus.

The pH of all of the biochar products with the exception of chicken litter and pine shavings was higher than their respective feedstocks. The pH of pine shavings biochar was unchanged while the pH of the poultry litter biochar was lower than the poultry litter feedstock.

Except for poultry litter, miscanthus, and cotton gin trash, the EC of the feedstocks ranged from 0.1 $dS \cdot cm^{-1}$ for mixed hardwoods to 0.7 $dS \cdot m^{-1}$ for rice hulls (Table 3). The poultry litter, miscanthus, and cotton gin trash feedstocks had higher EC values of 33.7, 2.2, and 6.0 $dS \cdot m^{-1}$, respectively. Except for poultry litter, the EC of the resulting biochar products were not significantly different from their respective feedstocks. The EC of poultry litter biochar was lower than the EC of the poultry litter feedstock but higher than all other biochar products. The CEC of the feedstocks ranged from 0.08 meq/g for the mixed hardwoods to 13.2 meq/g for poultry litter (Table 3). Except for poultry litter, the CEC of the resulting biochar products were not significantly different from their respective feedstocks. The CEC of poultry litter biochar was higher than the CEC of the poultry litter feedstock and at 19.0 meq/g, the highest CEC of all products tested was for the poultry litter biochar.

The NH_4^+ of the feedstocks ranged from a low of 0.2 $mg \cdot L^{-1}$ for the mixed hardwoods to 70.3 $mg \cdot L^{-1}$ for the poultry litter (Table 3). Except for poultry litter and cotton gin trash, the NH_4^+ concentration of the resulting biochar products was not different from their respective feedstocks. For poultry litter and cotton gin trash, the resulting biochar products had lower NH_4^+ concentrations than

Table 1. Total macroelement concentration from various agriculture byproduct feedstocks and their resulting biochar products.

Component	Status[z]	N (% wt/wt)[y]	P (mg·L^{-1})[y]	K (mg·L^{-1})	Ca (mg·L^{-1})	Mg (mg·L^{-1})	S (% wt/wt)
Poultry litter	Feedstock	2.70	36.74	17,740	15,226	4,237	0.37
Poultry litter	Biochar	3.57	51.08	18,391	25,203	4,586	0.56
Mixed hardwoods	Feedstock	0.18	41.72	924	874	190	0.03
Mixed hardwoods	Biochar	0.71	125.93	1,985	2,091	457	0.05
Miscanthus	Feedstock	0.63	5.27	7,505	2,971	816	0.05
Miscanthus	Biochar	1.09	9.01	17,007	6,631	1,844	0.05
Cotton gin trash	Feedstock	0.99	21.70	17,546	6,747	1,884	0.09
Cotton gin trash	Biochar	1.37	31.45	13,778	12,079	2,667	0.06
Switchgrass	Feedstock	0.43	2.64	1,413	2,716	836	0.06
Switchgrass	Biochar	0.86	4.49	2,171	6,743	2,041	0.04
Rice hull	Feedstock	0.39	4.21	2,270	1,054	228	0.01
Rice hull	Biochar	0.46	5.32	2,849	2,078	340	0.02
Pine shavings	Feedstock	0.14	2.64	784	1,127	341	0.00
Pine shavings	Biochar	0.55	9.56	3,256	4,780	681	0.02
Significance		***	***	***	***	***	***
LSD (α = 0.05)[x]		0.11	3.60	802	1,186	175	0.08

[z]Feedstocks ground to particle sizes of 10 to 20 mm (0.39 to 0.79 inch) in diameter. Biochar was produced in 1-gal (3.8 L) cylindrical metal containers at 400 °C (752.0 °F) with a residence time of 2 h.
[y]Percent was on a dry weight basis and mg·L^{-1} was determined using 0.5 mg (1.76×10^{-5} oz) of dry mass per 10 mL (0.34 fl oz) of Mehlich 3 extractant solution; N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, S = sulfur; 1 mg·L^{-1} = 1 ppm.
[x]Significant differences among means within columns determined using least significant difference (LSD) mean separation test.
***Significant at $P > F$ of 0.001.

Table 2. Total microelement concentration from various agriculture byproduct feedstocks and their resulting biochar products.

Component	Status[z]	B (mg·L^{-1})[y]	Cu (mg·L^{-1})	Fe (mg·L^{-1})	Mn (mg·L^{-1})	Mo (mg·L^{-1})	Na (mg·L^{-1})	Zn (mg·L^{-1})
Poultry litter	Feedstock	928.6[x]	419.24	603.67	330.53	2.61	4,822	403.3
Poultry litter	Biochar	889.2	415.35	621.72	412.7	2.74	6,966	552.4
Mixed hardwoods	Feedstock	147.4	5.47	21.20	12.6	0.09	124	7.57
Mixed hardwoods	Biochar	684.3	3.34	45.84	36.6	0.03	154	6.34
Miscanthus	Feedstock	66.3	13.10	55.54	44.6	0.56	100	15.15
Miscanthus	Biochar	55.5	9.14	86.25	101.9	1.58	108	28.89
Cotton gin trash	Feedstock	235.8	5.10	222.78	26.2	0.37	207	10.76
Cotton gin trash	Biochar	961.7	15.61	743.11	61.9	0.03	572	25.16
Switchgrass	Feedstock	93.9	7.30	71.57	27.9	0.09	129	6.51
Switchgrass	Biochar	115.6	4.52	112.12	66.9	0.17	222	12.12
Rice hull	Feedstock	182.8	40.47	51.93	127.1	0.26	59	9.29
Rice hull	Biochar	147.9	23.15	106.75	240.9	0.32	70	20.32
Pine shavings	Feedstock	53.4	3.25	41.78	159.9	0.02	46	11.40
Pine shavings	Biochar	107.7	14.63	201.36	88.5	0.00	84	19.96
Significance		***	***	***	***	***	***	***
LSD (α = 0.05)[x]		28.56	18.62	78.96	16.36	0.17	528	24.7

[z]Feedstocks ground to particle sizes of 10 to 20 mm (0.39 to 0.79 inch) in diameter. Biochar was produced in 1-gal (3.8 L) cylindrical metal containers at 400 °C (752.0 °F) with a residence time of 2 h.
[y]Concentration was determined using 0.5 mg (1.76×10^{-5} oz) of dry mass per 10 mL (0.34 fl oz) of Mehlich 3 extractant solution; B = boron, Cu = copper, Fe = iron, Mn = manganese, Mo = molybdenum, Na = sodium, Zn = zinc; 1 mg·L^{-1} = 1 ppm.
[x]Significant differences among means within columns determined using least significant difference (LSD) mean separation test.
***Significant at $P > F$ of 0.001.

their feedstocks. Except for poultry litter, the NO_3^- ranged from 0.1 to 0.7 mg·L^{-1} in the feedstocks (Table 3). The poultry litter feedstock contained 16.2 mg·L^{-1} NO_3^-. There was no difference in NO_3^- concentrations between the feedstocks and their resulting biochar products.

The P of the feedstocks ranged from a low of 0.3 mg·L^{-1} for the mixed hardwoods to 126 mg·L^{-1} for the poultry litter (Table 3). The P concentration in the biochar made from poultry litter and pine shavings was higher than the P concentration in the respective feedstocks. In contrast, the P in the biochar made from miscanthus was lower than the P in the miscanthus feedstock. The biochar made from poultry litter had the highest P of all the biochar products. There were no other differences in the P concentrations between the biochar products and their respective feedstocks. The K of the feedstocks ranged from a low of 23 mg·L^{-1} for the mixed hardwoods to 4902 mg·L^{-1} for the poultry litter (Table 3). The K concentration in the biochar made from poultry litter was higher than

Table 3. The pH, electrical conductivity (EC), cation-exchange-capacity (CEC), and water-extractable primary macroelement concentration from various agriculture byproduct feedstocks and their resulting biochar products.

Component	Status[z]	pH	EC ($dS \cdot m^{-1}$)[y]	CEC (meq/g)[y]	NH_4^+ ($mg \cdot L^{-1}$)[y]	NO_3^- ($mg \cdot L^{-1}$)	P ($mg \cdot L^{-1}$)	K ($mg \cdot L^{-1}$)
Poultry litter	Feedstock	8.7	33.7[x]	13.2[x]	70.3[x]	16.2	126	4,902
Poultry litter	Biochar	6.9	30.3	19.0	0.0	16.4	373	5,684
Mixed hardwoods	Feedstock	5.3	0.1	0.08	0.2	0.1	0.3	23
Mixed hardwoods	Biochar	5.9	0.1	0.09	0.0	0.0	1.2	17
Miscanthus	Feedstock	5.4	2.2	1.87	17.6	0.5	67.4	375
Miscanthus	Biochar	9.3	1.7	1.09	0.5	0.1	4.4	379
Cotton gin trash	Feedstock	5.6	6.0	3.39	74.1	0.7	71.6	939
Cotton gin trash	Biochar	7.0	4.7	2.68	20.5	0.8	55.6	763
Switchgrass	Feedstock	5.6	0.6	0.54	25.4	0.3	18.3	76
Switchgrass	Biochar	7.6	0.2	0.18	0.1	0.1	3.8	25
Rice hull	Feedstock	6.0	0.7	0.56	17.3	0.1	33.5	194
Rice hull	Biochar	7.2	0.2	0.20	0.3	0.1	6.8	54
Pine shavings	Feedstock	4.6	0.3	0.28	0.8	0.1	8.4	33
Pine shavings	Biochar	4.6	0.9	0.91	12.2	0.2	60.6	228
Significance		***	***	***	***	***	***	***
LSD ($\alpha = 0.05$)[x]		0.2	2.5	1.1	30.3	7.8	42.4	343.5

[z]Feedstocks ground to particle sizes of 10 to 20 mm (0.39 to 0.79 inch) in diameter. Biochar was produced in 1-gal (3.8 L) cylindrical metal containers at 400 °C (752.0 °F) with a residence time of 2 h. Values determined using a 1:1.5-deionized water saturated media extract method.
[y]NH_4^+ = ammonium, NO_3^- = nitrate, P = phosphorus, K = potassium; 1 $dS \cdot m^{-1}$ = 1 mmho/cm, 1 meq/g = 1 $mol \cdot kg^{-1}$, 1 $mg \cdot L^{-1}$ = 1 ppm.
[x]Significant differences among means within columns determined using least significant difference (LSD) mean separation test.
***Significant at $P > F$ of 0.001.

the K concentration in the poultry litter feedstock, and the poultry litter biochar had the highest K of the biochar products. There were no other differences in the K concentrations of the biochar products and their respective feedstocks.

The Ca of the feedstocks ranged from a low of 3.1 $mg \cdot L^{-1}$ for the mixed hardwoods to 111.4 $mg \cdot L^{-1}$ for the miscanthus (Table 4). The Ca in the biochar products ranged from 7.1 $mg \cdot L^{-1}$ for rice hulls to 339.7 $mg \cdot L^{-1}$ for the poultry litter biochar. The Ca concentration in the biochar made from poultry litter was higher than the Ca concentration in the poultry litter feedstock. In contrast, the Ca in the biochar made from miscanthus was lower than the miscanthus feedstock. There were no other differences in the Ca concentrations of the biochar products and their respective feedstocks. The Mg of the feedstocks ranged from 1.2 $mg \cdot L^{-1}$ for the mixed hardwoods to 64.5 $mg \cdot L^{-1}$ for cotton gin trash (Table 4). The Mg of the biochar products ranged from 1.0 $mg \cdot L^{-1}$ for the mixed hardwoods to 321 $mg \cdot L^{-1}$ for the poultry litter biochar (Table 4). The SO_4^{2-} of the feedstocks ranged from 2 $mg \cdot L^{-1}$ for the mixed hardwoods and the pine shavings to 3632 $mg \cdot L^{-1}$ for poultry litter. The SO_4^{2-} of the biochar products ranged from 3 $mg \cdot L^{-1}$ for the mixed hardwoods to 6005 $mg \cdot L^{-1}$ for the poultry litter biochar (Table 4). The Ca and SO_4^{2-} in the poultry litter biochar were higher than the poultry litter feedstock. There were no other differences in the Ca, Mg, and SO_4^{2-} concentrations of the biochar products and their respective feedstocks.

The highest B concentrations occurred in the poultry litter for both the feedstocks and resulting biochar products (Table 5). The B concentration was lower in the biochar made from poultry litter and mixed hardwoods than in their respective feedstocks. However, for all other materials the feedstocks and resulting biochar products had similar B concentrations. The highest Cl concentrations occurred in the poultry litter for both the feedstocks and resulting biochar products (Table 5). The Cl concentration was higher in the biochar made from poultry litter than the poultry litter feedstock. In contrast, the biochar made from cotton gin trash had a lower Cl concentration than the original cotton gin trash feedstock. For all other materials the feedstocks and resulting biochar products had similar Cl concentrations. The poultry litter feedstock and the resulting poultry litter biochar had higher Cu, Fe, Mn, Mo, Na, and Zn concentrations than any of the other feedstocks or resulting biochar products (Table 5). The biochar made from poultry litter had lower concentrations of Cu, Fe, MN, and Mo than the resulting poultry litter biochar. In contrast, the poultry litter biochar had higher Na and Zn concentrations that the poultry litter feedstock.

Discussion

Total mineral element concentration varied widely among both the biochar products and their respective feedstocks. Other researchers have also reported wide variations in mineral element concentration among different biochar products made from different feedstocks (Bates, 2010; Dumroese et al., 2011). Most researchers have reported that total mineral nutrients in biochar products were higher than in the feedstock used to produce the biochar products (Judd, 2016). This has typically been explained in that the process of making the biochar reduced the product weight and thus the remaining mineral elements made a higher proportion by weight of the resulting biochar products. In most cases, the results of this research were in agreement with these reports. The notable exceptions were that the P in biochar decreased as compared with the feedstock for cotton gin trash and the B decreased in the biochar as compared with the feedstock for the poultry litter. Observations of high product variability and nutrient data fluctuations in biochars presented in this work further illustrate the need for current and future researchers and potential manufacturers (product developers) to pay caution in the reliability of different biochars and the expected or anticipated results of their use.

When evaluating the water extractable nutrient concentration, the NH_4^+ concentrations of the biochar products were unchanged or decreased as compared with their respective feedstocks. This finding was consistent with previous research reports and was attributed to the volatilization of NH_4^+ in the manufacturing process. In contrast to NH_4^+, the NO_3^- concentrations were unchanged between a feedstock and its resulting biochar product. The water-extractable concentrations of all other macro- and micronutrients increased, decreased, or remained unchanged depending on the feedstock. Therefore, the concentration of mineral elements immediately available for plant uptake (water extractable) varied widely based on the feedstock used to make the biochar and these findings concurred with those reported by other researchers (Altland and Locke, 2012, 2014; Bates, 2010).

With the exception of P, the total concentration of all macro- and micronutrients were higher in the total elemental analysis than the water-extractable analysis. For the poultry litter and cotton gin trash biochar products, the total P was not higher than the water-extractable P. Both the poultry litter and cotton gin trash were feedstocks that were highly variable and composed of several nonuniform components (poultry feces, rice hulls, cotton plant stems, and burrs). The variability in the feedstock could have resulted in nonuniform biochar products and thus resulted in the differences in P concentrations observed for these two products.

Poultry litter biochar had higher concentrations of mineral elements than all of the other types of biochar

Table 4. The water-extractable secondary macroelement concentrations from various agriculture byproduct feedstocks and their resulting biochar products.

Component	Status[y]	Ca ($mg \cdot L^{-1}$)[z]	Mg ($mg \cdot L^{-1}$)	SO_4^{2-} ($mg \cdot L^{-1}$)
Poultry litter	Feedstock	85.3[x]	7.6	3,632
Poultry litter	Biochar	339.7	321.0	6,005
Mixed hardwoods	Feedstock	3.1	1.2	2
Mixed hardwoods	Biochar	7.9	1.0	3
Miscanthus	Feedstock	111.4	41.9	8
Miscanthus	Biochar	14.5	5.9	33
Cotton gin trash	Feedstock	89.2	64.5	335
Cotton gin trash	Biochar	69.3	45.1	228
Switchgrass	Feedstock	27.9	24.3	9
Switchgrass	Biochar	16.2	4.4	4
Rice hull	Feedstock	3.8	5.6	16
Rice hull	Biochar	7.1	3.3	4
Pine shavings	Feedstock	23.0	9.5	2
Pine shavings	Biochar	16.6	29.6	4
Significance		***	***	***
LSD ($\alpha = 0.05$)[x]		34.6	36.2	828

[z]Feedstocks ground to particle sizes of 10 to 20 mm (0.39 to 0.79 inch) in diameter. Biochar was produced in 1-gal (3.8 L) cylindrical metal containers at 400 °C (752.0 °F) with a residence time of 2 h. Values determined using a 1:1.5-deionized water saturated media extract method.
[y]Ca = calcium, Mg = magnesium. SO_4^{2-} = sulfate; 1 $mg \cdot L^{-1}$ = 1 ppm.
[x]Significant differences among means within columns determined using least significant difference (LSD) mean separation test.
***Significant at $P > F$ of 0.001.

Table 5. The water-extractable microelement concentration from various agriculture byproduct feedstocks and their resulting biochar products.

Component	Status[z]	B ($mg \cdot L^{-1}$)[y]	Cl ($mg \cdot L^{-1}$)	Cu ($mg \cdot L^{-1}$)	Fe ($mg \cdot L^{-1}$)	Mn ($mg \cdot L^{-1}$)	Mo ($mg \cdot L^{-1}$)	Na ($mg \cdot L^{-1}$)	Zn ($mg \cdot L^{-1}$)
Poultry litter	Feedstock	5.1[x]	2,585	54.7	23.1	2.3	2.6	1,426	19.5
Poultry litter	Biochar	4.4	3,294	19.3	4.4	1.8	0.8	2,389	3.1
Mixed hardwoods	Feedstock	1.9	5.2	0.0	0.0	0.0	0.0	3.1	0.0
Mixed hardwoods	Biochar	0.9	4.6	0.0	0.0	0.0	0.0	2.6	0.0
Miscanthus	Feedstock	0.2	171	0.0	0.1	2.0	0.0	2.0	0.4
Miscanthus	Biochar	0.0	250	0.0	0.0	0.0	0.0	2.6	0.0
Cotton gin trash	Feedstock	0.5	593	0.1	0.2	0.2	0.0	14.8	0.5
Cotton gin trash	Biochar	0.4	326	0.0	0.2	0.1	0.0	35.6	0.1
Switchgrass	Feedstock	0.0	37	0.0	0.1	0.4	0.0	8.7	0.0
Switchgrass	Biochar	0.0	7.1	0.0	0.0	0.0	0.0	3.6	0.0
Rice hull	Feedstock	0.2	65.4	0.1	0.1	3.3	0.0	5.5	0.1
Rice hull	Biochar	0.0	10.7	0.0	0.1	2.3	0.0	3.6	0.0
Pine shavings	Feedstock	0.0	4.5	0.0	0.0	4.4	0.0	2.4	0.2
Pine shavings	Biochar	0.3	11.5	0.0	0.2	2.4	0.0	5.0	0.3
Significance		***	***	***	***	***	***	***	***
LSD ($\alpha = 0.05$)[x]		0.4	169	9.0	3.5	0.5	0.5	221	1.0

[z]Feedstocks ground to particle sizes of 10 to 20 mm in diameter. Biochar was produced in 1-gal (3.8 L) cylindrical metal containers at 400 °C (752.0 °F) with a residence time of 2 h. Values determined using a 1:1.5-deionized water saturated media extract method.
[y]B = boron, Cl = chloride, Cu = copper, Fe = iron, Mn = manganese, Mo = molybdenum, Na = sodium, Zn = zinc; 1 $mg \cdot L^{-1}$ = 1 ppm.
[x]Significant differences among means within columns determined using least significant difference (LSD) mean separation test.
***Significant at $P > F$ of 0.001.

in this study. In fact, poultry litter biochar contained concentrations of P, K, Cu, Fe, and Zn that could be high enough to cause phytotoxicity or negatively impact crops being grown using the product. These concentrations of mineral elements would require that poultry litter biochar be used in small amounts in a root substrate. The other types of biochar products had varying concentrations of water-extractable mineral elements. In these cases, the concentrations of P, and K in particular would potentially be too high for most greenhouse crops, but if blended with other components, the concentrations of mineral nutrients would be within recommended ranges for most greenhouse crops. One point to mention regarding the high nutrient concentrations of substrate components (biochars in this case) at 100% is that those nutrient amounts may or may not suggest the concentration that would be plant-available once amended in a substrate as a component percentage. Properties (physical or chemical) of components do not always yield summation results in a blended substrate. This is a key point to be aware of regarding the effect of substrate components and amendments before and after blending/mixing.

Previous researchers have reported that the feedstock had a significant impact of the pH of the resulting biochar product (Fornes et al., 2015; Hass et al., 2012; Mukherjee et al., 2011; Nemati et al., 2015; Spokas et al., 2012). In fact, the pH of biochar products in this research ranged from 4.6 to 9.3. This wide range in pH values could require growers to make adjustments in their substrate components or in their limestone amendment program to compensate for the differences in pH and the effect that the different biochar products would have on the root substrates. It is not known (reported in the literature) what the effect of biochar is on the pH of horticultural substrates when amended as a substrate component.

Similar to the mineral element concentration, the EC of the biochar products varied widely. The EC was very high for poultry litter biochar, thus making it potentially unsuitable for use in a root substrate unless used in only very limited amounts. The high EC in poultry litter biochar has been reported in other findings (Song and Guo, 2012). The cotton gin trash biochar also had a higher than recommended EC, but it was at a concentration that if it were blended with other components, the EC could be brought to a desirable concentration. All other biochar products had EC concentrations within recommended ranges for root substrates.

Based on these results, poultry litter-based biochar could be problematic due to their very high nutrient concentration and resulting EC. Other researchers have reported similar results with manure-based biochar products (Hass et al., 2012; Song and Guo, 2012). This could introduce management issues and limit the use of manure-based biochar products. The high carbon feedstock biochar products had much lower nutrient concentrations and if blended with other components could likely be useable as substrate components easier than some of the materials with very high chemical properties (EC, pH, etc.). However, even within this group of biochars made from agricultural byproducts common in the southern United States, many of the chemical properties such as EC, pH, and the primary and secondary macronutrients varied considerably and would need to be considered when designing and managing a root substrate.

Researchers have noted that it is inappropriate to refer to composts as single entities and to make recommendations that composts can be used in substrates is inappropriate due to the high degree of variability that occurs in composts depending upon the compost feedstock and the composting process (Rosen et al., 1993; Sterrett, 2000; Taylor and Jackson, 2014). The results of this research emphasize that the same issue occurs with biochar products. Even when made using the same process, the biochar products had very different chemical properties depending on the feedstock. Therefore, biochar should not be referred to as a single entity and, blanket recommendations for the use and performance of biochar products as root substrates components cannot be made without specific information regarding all variables related not only to the methods of production but also the specific nature of the feedstock used in its production. The high concentration variability will also require the end users such as greenhouse and nursery crop growers to have knowledge of their suppliers' feedstocks and specific production processes and routinely test the biochar products before use.

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