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High rates of gasified rice hull biochar affect geranium and tomato growth in a soilless substrate

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ABSTRACT

Gasified rice hull biochar (GRHB) is a by-product of rice production, where rice hulls are gasified to generate energy for other aspects of rice processing. Other research studies have shown that GRHB up to 10% (v/v) in a soilless substrate can provide much, but not all, of a potted floriculture crops' phosphorus and potassium needs. The objective of this research was to determine the effect of higher GRHB rates on floriculture crop nutrition and growth. Two experiments were conducted with GRHB rates ranging from 0 to 30% (v/v) of a soilless peat moss-based substrate. Geranium (Pelargonium × hortorum "Maverick Red") and tomato (Solanum lycopersicum "Megabite") were grown in 10-cm diameter pots with amended substrates. Addition of GRHB up to 30% affected the physical properties of the peat moss-based substrate by increasing container capacity (CC) and decreasing unavailable water (UAW). Summarizing across the two experiments, amending a peat moss substrate with 15–20% GRHB provided sufficient phosphorus (P) and potassium (K) for production of geranium and tomato in soilless substrates over a 5- to 6-week production cycle. However, GRHB did not provide a sufficient source of micronutrients to support crop growth. Geranium responded negatively to high rates (>10%) with reduced shoot and root growth, while tomato responded positively to higher rates with increased shoot growth. Higher rates of GRHB (>10%) can be recommended for some crops, but not all.

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Introduction

New amendments are routinely evaluated for their ability to improve chemical, physical, and biological properties of commercial greenhouse and nursery substrates. Over the past five years, interest in biochar materials has increased due to greater interest in the use of pyrolysis for energy production. Modern pyrolysis systems are used to extract liquid and gas petroleum products from biomass or manure for fuel or other chemical products. Biochar is the charred organic matter that remains after pyrolysis.

The influence of biochar in mineral soil systems has been studied and reviewed extensively (Lehmann et al. 2011; Spokas et al. 2011). Some commonly cited beneficial impacts of biochar are improved crop growth in highly weathered or sandy soils (Lehmann et al. 2003; Novak et al. 2009), increased soil pH (Novak et al. 2009), increases in beneficial microbial populations (Lehmann et al. 2011), increased mycorrhizal associations (Warnock et al. 2007), and improved nutrient retention (Clough and Condron 2010).

Recent work in soilless substrates for horticultural crops has reported similar benefits of biochar use in container substrates. Vaughn et al. (2013) showed that biochar derived from hardwood pellets or

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pelletized wheat (*Triticum* spp.) straw improved growth of tomato (*Solanum lycopersicum* L.) and marigold (*Tagetes erecta* L.) when incorporated at rates up to 15% (by vol.) in a peat moss substrate. Taking advantage of the typically high pH of most biochar materials, Zaccheo, Crippa, and Cattivello (2014) showed that additions of pine (*Pinus* spp.)-based biochar up to 40% (by vol.) could be used to increase pH of peat moss and function as an alternative to lime in soilless substrates for pH adjustment. Zwart and Kim (2012) showed that a pine-based biochar has the potential to alleviate disease progression and physiological stress caused by phytophthora canker (*Phytophthora cinnamomi* and *Phytophthoracactorum*). Headlee, Brewer, and Hall (2014) showed that peat moss amended with 25% biochar had higher cation exchange capacity than peat moss alone and as a result, provided greater potassium (K) retention and availability.

The mineral composition of biochar tends to reflect the parent biomass material, but at much higher concentrations once carbon (C), hydrogen (H), and oxygen (O) have been burned off. Evans, Buck, and Sambo (2011) showed that parboiled rice (*Oryza sativa* L.) hulls have relatively high phosphorus (P) and K concentrations, to the extent that the addition of parboiled rice hulls should be accounted for when developing a fertility program. In a column study, Altland and Locke (2013a) showed that a 10% amendment (by vol.) of gasified rice hull biochar (GRHB) in 600 cm^3 of a peat moss substrate provided 30.7 mg phosphate (PO_4^{2-}), and thus there was enough P to satisfy the needs of most floriculture species. Subsequently, several greenhouse experiments demonstrated that GRHB incorporated up to 10% (by vol.) into a peat moss substrate does not contain sufficient P to sustain floriculture crops through a 6- to 8-week production cycle in 10-cm diameter pots (Altland and Locke 2013b; Locke, Altland, and Ford 2013). The objective of this research was to determine if higher rates of GRHB could provide the total P and K needs of floriculture crops throughout a 6- to 8-week production period, as well as quantify any other effects it might have on crop growth and development.

Materials and methods

A commercially available form of GRHB (CharSil, Scott-Glenn, Co, Birmingham, AL) was used as an amendment, with physical and chemical properties previously discussed (Locke, Altland, and Ford 2013). This form of biochar is generated by passing rice hulls through a gasifier at 815–871°C under substoichiometric conditions, with a residency time of 2–3 s.

Plant culture

The experiments were conducted in a glasshouse on the campus of the University of Toledo (Toledo, OH). Throughout the experiments, natural light was supplemented with paired 250-W high pressure sodium and 400-W mercury vapor lights when outside ambient light levels dropped below 200 μmol m^{-2} s^{-1}. Greenhouse heating and cooling set points were 21 and 26°C, respectively.

A peat moss and perlite potting mix (Sunshine Mix #2, Sun Gro Horticulture Canada Ltd., Seba Beach, AB, Can.) was selected as the base substrate for the studies. The base substrate contained no incorporated N, P, K, or micronutrient fertilizers, but was pre-incorporated with a proprietary quantity of gypsum and dolomitic limestone. Geranium (*Pelargonium* × *hortorum*"Maverick Red") and "Megabite" tomato seedlings were germinated in 288-cell plug trays containing the base substrate and grown for 3 weeks prior to transplant.

Experiment 1

The treatment design for this experiment was a 2 × 3 augmented factorial arrangement with two fertilizer treatments, three GRHB amendment rates, and augmented with a control group. The control group was fertilized with a commercial complete fertilizer with micronutrients (Jack's 20N-4.4 phosphorus (P)-16.6 potassium (K)-0.15 magnesium (Mg)-0.02 boron (B)-0.01copper (Cu)-0.1iron (Fe)-0.05 manganese (Mn)-0.01molybdenum (Mo)-0.05 zinc (Zn), JR Peters, Inc., Allentown, PA) at a rate of 100 mg L^{-1} N, hereafter referred to as the NPK-controls. Three treatments consisted of the base

substrate amended with GRHB at 10, 20, or 30% (v/v), fertilized with 100 mg L^{-1} N using ammonium nitrate (AN). Three additional treatments consisted of the base substrate amended with a commercial micronutrient package (Micromax, The Scotts Co., Marysville, OH) at 0.9 kg m^{-3}, along with GRHB at 10, 20, or 30%, and fertilized with 100 mg L^{-1} N AN. Geraniums were transplanted as a single plug per 10-cm diameter (approx. 600 cm^3 volume) pot on 9 November 2012. Plants were fertigated as needed by hand-pouring from a glass beaker, with approximately three fertigation events each week. A 15-cm diameter clear vinyl saucer (Hummert Int., Earth City, MO) was placed beneath each container to capture leachate and allow it to be re-absorbed by the substrate, thus avoiding any nutrient loss via leaching. There were ten single-pot replications per treatment arranged in a completely randomized design, with five replications harvested each at 3 and 6 weeks after potting (WAP).

Substrate physical properties were determined for each substrate immediately after mixing. Substrates were packed in 347-cm^3 aluminum cores (7.6 cm tall by 7.6 cm i.d.) according to methods described by Fonteno and Bilderback (1993). There were three replications for each amended substrate. Aluminum cores were attached to porometers (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, NC) for the determination of air space (AS). Cores were weighed, oven-dried for 4 days at (72°C), and weighed again to determine container capacity (CC). Total porosity (TP) was calculated as the sum of AS and CC. Bulk density (D_b) was determined using oven-dried (72°C) substrate in 347-cm^3 cores. Unavailable water (UAW), held in the substrate at $\geq$1.5 MPa, was determined with 116-cm^3 cores (2.5 cm tall by 7.6 cm i.d.) in a porous ceramic pressure plate extractor via a procedure described by Milks, Fonteno, and Larson (1989). Unavailable water was determined with four replications per substrate.

At 3 and 6 WAP, five replicates from every treatment were destructively harvested. Containers were subjected to the pour-through technique (Yeager et al. 2007) in order to collect a 50-mL sample of the substrate solution for the measurement of pH, electrical conductivity (EC), and nutrient analysis. Substrate solutions were immediately measured for pH and EC then frozen until nutrient analysis was performed. At the time of nutrient analysis, samples were thawed and filtered through GF/F binder-free borosilicate glass fiber filter paper (Whatman Ltd., Kent, UK) to remove particles larger than 0.7 μm. The filtrate was poured into 5-mL autosampler vials, capped, and analyzed on an ICS 1600 (Ion Chromatography System, Dionex, Bannockburn, IL) for concentrations of nitrate (NO_3^-), ammonium (NH_4^+), phosphate $(PO_4^{2})^-$, K, calcium (Ca), magnesium (Mg), and sulfate (SO_4^{2-}). Recently matured foliage was harvested for foliar nutrient analysis (Mills and Jones 1996), rinsed with deionized water, and oven-dried at 55°C for 3 days. Samples were ground in a mill (Tecator Cyclotec AB, Hogenas, Sweden) through a 0.5-mm screen. Foliar N was determined with a nitrogen analyzer (PerkinElmer Series II CHNS/O Analyzer, PerkinElmer Instruments, Shelton, CT). Other macronutrients and micronutrients were determined with optical emission spectroscopy (iCAP 6000 Spectrophotometer, Thermo Fisher Scientific, Waltham, MA). Immediately after leaf tissue harvest, shoot dry weight (SDW) was determined by removing the shoot portion of the plant, oven drying at 55°C for 3 days, and weighing.

Experiment 2

The second experiment was conducted similar to the previous experiment with the following exceptions. There were five substrate treatments, all amended with the same commercial micronutrient package at 0.9 kg m^{-3}, and GRHB amended at 0, 5, 10, 15, or 20%. These five treatments were fertilized with AN at 100 mg L^{-1} N. A sixth treatment was a non-amended NPK-control group, similar to the previous experiment, fertilized with the same complete commercial fertilizer at a rate of 100 mg L^{-1} N. Geranium and tomato plugs were potted on 4 February 2013, and data were collected 3 and 5 WAP. There were 12 single-plant replications per treatment and species arranged in a completely randomized design, with six replications from each species destructively harvested 3 and 5 WAP. Geranium and tomato were randomized separately.

Data were subjected to analysis of variance using the general linear model (GLM) procedure in SAS (SAS Institute Inc., Cary, NC). Least significant difference (LSD) values were determined with Fisher's

test where $\alpha = 0.05$. Where appropriate, rate response across GRHB rates was determined with orthogonal contrast statements within the GLM procedure.

Results and discussion

GRHB affected physical properties of amended substrates (Table 1). Increasing amendment of GRHB resulted in a quadratic rate response in AS. AS initially declined with 10% GRHB and increased slightly (although not significantly) with up to 30% GRHB. Amendment with 30% GRHB had similar AS to non-amended controls. Conversely, CC increased and then decreased quadratically with increasing GRHB amendment. Container capacity was higher in all GRHB-amended substrates compared to non-amended controls. Others (Bi and Evans 2009; Vaughn et al. 2013) likewise showed a decrease in AS and concomitant increase in CC with additions of biochar. Unavailable water was lower for all GRHB-amended substrates compared to the non-amended control. Increased CC and decreased UAW suggest better water relations in GRHB-amended substrates. These results concur with previous work (Altland and Locke 2013b) that showed increased CC and decreased UAW in GRHB-amended substrates at rates up to 10% GRHB. TP increased linearly with increasing GRHB amendment. Total porosity is the sum of AS and CC, and thus the inverse relationship of AS and CC resulted in relatively minor differences in TP. Bulk density increased linearly with increasing GRHB amendment. The GRHB used in this experiment had a bulk density of 0.32 g cm^{-3} compared to 0.10 g cm^{-3} for the base substrate, and thus resulted in predictable small incremental increases in bulk density with increasing rates (Pokorny, Gibson, and Dunavent 1986).

Substrate pH was greater in all GRHB-amended substrates compared to the NPK-control (Table 2). Most biochar materials have inherently high pH (Bi and Evans 2009; Tian et al. 2012; Headlee, Brewer, and Hall 2014), to the extent that Zaccheo, Crippa, and Cattivello (2014) reported biochar could replace lime as a neutralizing agent in peat moss substrates. Although there was a significant interaction between micronutrient and GRHB rate at 3 WAP, substrate pH increased similarly with increasing GRHB rate in containers with and without micronutrients. Other research works have shown that GRHB rates up to 10% increase substrate pH of peat moss-based substrates slightly (Locke, Altland, and Ford 2013); however, the effect of fertilizer potential acidity can have a more powerful effect in suppressing pH (Altland and Locke 2013b). At 6 WAP, there was no significant interaction between micronutrients and GRHB rate ($p = 0.0561$), although main effects of both terms were significant ($p < 0.0001$). Substrate pH was lower among containers amended with micronutrients compared to those without, but increased with increasing GRHB rate. Similar to our results, Wright et al. (1999a, 1999b) reported a significant, although slight, decrease in pine bark substrate pH with additions of the same micronutrient package and rate used in our experiment.

Substrate EC at 3 WAP was greater in all GRHB-amended substrates compared to NPK-controls (Table 2). Substrate EC increased with increasing GRHB rate, but was affected by neither the addition of micronutrients ($p = 0.1252$) nor the interaction between micronutrients and GRHB ($p = 0.3544$).

Table 1. Physical properties of a commercial peat-based substrate amended with 0–30% gasified rice hull biochar (GRHB).

GRHB amendment	Air space	Container capacity	Unavailable water	Total porosity	Bulk density
		(%)			(g cm^{-3})
0	14.6	69.8	18.3	84.4	0.100
10	9.0	77.6	14.2	86.6	0.129
20	10.7	75.8	15.0	86.5	0.125
30	11.7	74.6	15.1	86.4	0.130
Rate response[z]	Q^{**}	$L^{**}Q^{***}$	$L^{**}Q^{**}$	L^{*}	$L^{***}Q^{***}$
$LSD_{0.05}$[y]	3.0	2.2	1.4	1.8	0.005

[z]Indicates a significant linear (L) or quadratic (Q) rate response to GRHB rate, where *, **, or *** represents p-values of 0.05, 0.01, or 0.001, respectively.
[y]Least significant difference within a column, where $\alpha = 0.05$.

Table 2. Substrate pH, electrical conductivity (EC), and pour-through extractable nutrients at 3 and 6 weeks after potting (WAP) from substrates amended with 0 or 0.9 kg m^{-3} Micromax micronutrients and 0–30% gasified rice hull biochar (GRHB). A control group was fertilized with a complete water-soluble fertilizer containing all macronutrients and micronutrients.

Date	Micronutrient (kg m^{-3})	GRHB (%)	pH	EC mS cm^{-1}	Nitrate	Phosphate	Potassium	Calcium	Magnesium	Sulfate
					mg L^{-1}					
3 WAP	Control	0	6.2	1.3	312.3	59.6	50.0	81.5	169.6	434.8
	0	10	6.6	1.7	425.2	61.9	161.3	78.9	168.3	436.3
	0	20	7.0	2.2	449.8	155.6	410.7	56.8	142.0	446.4
	0	30	7.3	2.4	435.1	185.3	529.6	43.3	117.7	472.1
	0.9	10	6.7	1.7	219.9	32.2	139.7	101.5	211.8	837.4
	0.9	20	6.8	2.2	253.6	16.3	344.1	94.6	207.1	1017.3
	0.9	30	7.2	2.7	396.0	58.4	567.9	65.6	166.3	846.9
$LSD_{0.05}$[z]			0.1	0.3	90.7	30.5	61.7	15.6	27.5	182.0
Main effects			p-Value							
	Micronutrient		0.1192	0.1252	0.0001	0.0001	0.3460	0.0001	0.0001	0.0001
	GRHB		0.0001	0.0001	0.0185	0.0001	0.0001	0.0001	0.0001	0.3027
	Interaction		0.0001	0.3544	0.0209	0.0001	0.0636	0.2728	0.5005	0.2551
6 WAP	Control	0	6.6	0.5	36.0	10.9	6.5	17.4	29.0	127.4
	0	10	7.0	0.5	61.9	13.0	13.0	13.5	25.0	88.0
	0	20	7.4	0.5	79.8	22.8	27.4	12.8	23.4	84.1
	0	30	7.6	0.6	90.1	29.8	50.2	10.4	21.0	94.1
	0.9	10	6.8	0.5	13.0	8.5	7.8	17.4	25.8	133.9
	0.9	20	7.0	1.1	168.2	23.2	56.4	21.1	41.6	194.5
	0.9	30	7.3	1.2	144.0	34.3	83.5	19.6	39.8	286.2
$LSD_{0.05}$			0.1	0.4	107.3	7.8	35.3	6.3	12.3	104.1
Main effects			p-Value							
	Micronutrient		0.0001	0.0014	0.3403	0.9960	0.0698	0.0005	0.0014	0.0006
	GRHB		0.0001	0.0064	0.0646	0.0001	0.0005	0.6363	0.2961	0.1120
	Interaction		0.0561	0.0809	0.1630	0.2339	0.2400	0.3921	0.0617	0.1376

[z]Fisher's protected least significant difference value, where $\alpha = 0.05$.

At 6 WAP, EC was higher in substrates amended with micronutrients ($p = 0.0014$). Recommended EC levels for greenhouse substrates, determined via the pour-through method, range from 1.0 to 3.5 mS cm^{-1} for most floriculture crops, and 1.0 to 2.6 mS cm^{-1} for seed geranium (Cavins et al. 2000). While GRHB amendment increased substrate EC, levels were within or lower than those recommended for floriculture crops in.

Leachate ammonium concentrations were relatively low with few and minor treatment differences. Ammonium concentration averaged 9.6 mg L^{-1} at 3 WAP and 0.0 by 6 WAP (data not shown). Nitrate concentrations in leachates were affected by an interaction between micronutrient and GRHB amendment at 3 WAP (Table 2). Nitrate concentrations in substrates not amended with micronutrients were similar, and all were higher than NPK-controls. Substrates amended with micronutrients had higher leachate NO_3^- concentrations when amended with 30% GRHB compared to 10 or 20%. Differences in leachate NO_3^- concentration can be in part attributed to SDW (Table 3). There was a strong negative correlation between SDW and leachate NO_3^- concentration across all treatments ($R = -0.8766$, $n = 35$, data not shown). Larger plants absorbed more NO_3^- than smaller plants. By 6 WAP, there were no differences in leachate NO_3^- concentrations attributable to treatment. Phosphate concentrations in leachates increased with increasing GRHB amendment at 3 and 6 WAP, with and without micronutrient amendment. At 3 WAP, leachate PO_4^{2-} concentrations were lower in substrates amended with micronutrients compare to those without. By 6 WAP, micronutrient amendment did not affect either leachate PO_4^{2-} concentrations ($p = 0.9960$), or the interaction between micronutrient and GRHB rate ($p = 0.2339$). However, leachate PO_4^{2-} concentration increased with increasing GRHB amendment. Leachate K concentration increased with increasing GRHB amendment and was not affected by micronutrient addition at 3 or 6 WAP. This concurs with other research showing high PO_4^{2-} and K levels in

Table 3. Shoot dry weight and foliar tissue concentration in geranium (Pelargonium × hortorum "Maverick Red") at 3 and 6 weeks after potting (WAP) from substrates amended with 0 or 0.9 kg m^{-3} micromax micronutrients and 0–30% gasified rice hull biochar (GRHB). A control group was fertilized with a complete water-soluble fertilizer containing all macronutrients and micronutrients.

				Foliar tissue concentrations										
Date	Micronutrient (kg m^{-3})	GRHB (%)	Shoot dry weight (g)	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
				(%)						mg kg^{-1}				
3 WAP	Control	0	0.79	4.94	0.68	4.64	1.39	1.03	0.33	25.3	2.3	132.8	115.9	49.8
	0	10	0.56	4.10	0.73	5.24	1.11	0.96	0.32	12.1	1.1	76.5	262.2	20.6
	0	20	0.31	3.60	0.83	6.45	0.80	0.71	0.26	12.4	1.2	33.3	226.4	15.8
	0	30	0.31	2.44	0.55	5.24	0.43	0.33	0.16	6.6	1.7	23.2	65.2	10.0
	0.9	10	1.10	4.16	0.49	5.29	1.16	0.83	0.32	33.4	6.6	116.0	762.3	73.2
	0.9	20	0.87	3.98	0.54	6.40	1.15	0.86	0.32	34.9	6.0	109.7	887.5	59.1
	0.9	30	0.57	3.78	0.55	8.06	1.01	0.83	0.31	33.0	5.2	77.3	829.9	44.0
$LSD_{0.05}$[z]			0.16	0.28	0.07	0.49	0.13	0.08	0.03	3.3	1.2	23.3	119.3	0.3
Micronutrient			0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
GRHB			0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0058	0.5575	0.0001	0.0416	0.0001
Interaction			0.023	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0813	0.0775	0.0859	0.0116	0.0114
6 WAP	Control	0	2.69	2.34	0.31	2.02	0.82	0.66	0.23	13.1	2.0	34.1	54.9	20.8
	0	10	1.28	3.52	0.66	4.60	1.18	1.12	0.37	6.7	1.9	108.4	283.3	12.8
	0	20	0.66	3.18	0.70	6.34	0.73	0.72	0.24	7.3	1.3	18.5	246.3	11.3
	0	30	0.21	3.36	0.82	7.31	0.57	0.48	0.25	8.7	2.0	17.6	93.8	10.4
	0.9	10	3.66	2.14	0.25	2.56	0.82	0.58	0.17	17.7	3.9	38.9	507.0	33.7
	0.9	20	0.89	2.27	0.38	3.42	0.60	0.50	0.27	11.3	4.7	56.0	200.3	17.3
	0.9	30	1.26	2.07	0.48	4.53	0.55	0.46	0.26	9.8	4.6	50.6	326.6	21.0
$LSD_{0.05}$			1.31	0.42	0.14	0.93	0.18	0.16	0.11	5.6	2.1	46.3	207.2	6.7
Recommended minimum[y]				3.7	0.3	2.5	0.8	0.2	0.18	35	5	70	110	36
Micronutrient			0.0027	0.0001	0.0001	0.0001	0.0026	0.0001	0.1086	0.0021	0.0002	0.9824	0.0269	0.0001
GRHB			0.0007	0.6777	0.0020	0.0001	0.0001	0.0001	0.9081	0.2300	0.8480	0.0345	0.0254	0.0010
Interaction			0.0732	0.2365	0.6106	0.3399	0.0320	0.0003	0.0064	0.0485	0.5826	0.0029	0.1014	0.0091

[z]Fisher's protected least significant difference value, where $\alpha = 0.05$.
[y]Krug, Whipker, and McCall2010. Geranium leaf tissue nutrient sufficiency ranges by chronological age. Journal of Plant Nutrition 33:339–350.

solutions of substrates amended with GRHB (Altland and Locke 2013a). Leachate Ca and Mg levels responded similarly, in that both nutrients were influenced by the main effects of micronutrient amendment and GRHB, but not their interaction. Furthermore, both nutrients were in higher concentration in leachates from containers amended with micronutrients than those not amended, and both decreased in concentration with increasing GRHB rate. Higher Ca and Mg in substrates amended with micronutrients could be due to the presence of Ca and Mg sulfates in the micronutrient product. Calcium and Mg are known to bind with PO_4^{2-} to form insoluble minerals, dropping out of solution and thus not detectable in leachates. Increased Ca and Mg in treatments not amended with micronutrients, and decreasing Ca and Mg with increasing GRHB rate could be due to binding of these two metals with correspondingly higher PO_4^{2-} levels in those treatments. Leachate sulfates were highest in substrates amended with micronutrients, and not affected by GRHB ($p = 0.3207$). Higher sulfates in micronutrient-amended substrates are likely because the product used is composed primarily of sulfated micronutrients.

Shoot dry weights 3 WAP were greatest in geranium amended with 10% GRHB and micronutrients (Table 3). Increasing GRHB above 10% resulted in reduced shoot growth with and without micronutrients. By 6 WAP, geraniums grown in the NPK-control and 10% GRHB with micronutrients were similar in mass and greater than all other treatments. SDW was not affected by an interaction between micronutrient and GRHB amendments, but was affected by both main effects. Geraniums amended with micronutrients were larger than those without ($p = 0.0027$). Bi and Evans (2009) likewise reported that marigolds (*Tagetes patula* L.) grown in substrates containing 10–20% pulp mill ash had similar growth to control plants grown in the commercial substrate, while those grown in higher rates, 30–50% ash, had lower SDWs or root quality ratings compared to plants grown in the commercial substrate.

Foliar N was greatest in the non-amended control at 3 WAP (Table 3). Foliar N decreased with increasing GRHB amendment among plants with and without micronutrient amendment, but more so among plants without. By 6 WAP, foliar N was lower in plants fertilized with micronutrients compared to those without, and was similar to NPK-controls. Foliar N was not affected by GRHB rate at 6 WAP ($p = 0.6777$). At 3 WAP, foliar P was affected by an interaction between micronutrient and GRHB amendment ($p < 0.0001$). Foliar P was lower among plants amended with micronutrients compared to the NPK-control and those not amended with micronutrients. Nonetheless, all plants had foliar P concentrations higher than the minimum recommended level (Krug, Whipker, and McCall 2010). By 6 WAP, foliar P was similar among plants amended with micronutrients and the NPK-controls, all of which were lower than those not amended with micronutrients. Plants amended with micronutrients and 10% GRHB had foliar P concentrations slightly lower than recommended, while the concentrations of all other plants were above the recommended level. Foliar K levels varied by treatment at 3 and 6 WAP, but all were higher than recommended levels (except non-amended controls 6 WAP). By 6 WAP, foliar K among plants amended with micronutrients was lower than for those without.

Foliar Ca decreased with increasing GRHB amendment in containers with and without micronutrient amendment, at 3 and 6 WAP (Table 3). This corresponds to the decreasing levels of Ca observed in leachates (Table 2) collected at the same time as foliar samples were harvested. By 6 WAP, geraniums in substrates with greater than 10% GRHB had lower than recommended foliar Ca concentrations. Depressed levels of Ca could be the result of elevated K levels in GRHB, as Ca and K are reported to be antagonistic (Mills and Jones 1996). At 3 and 6 WAP, foliar Mg concentrations decreased with increasing GRHB in substrates not amended with micronutrients, but were similar among substrates amended with micronutrients. Despite treatment differences, all geraniums had higher than recommended foliar Mg concentrations throughout the experiment. Similar to foliar Mg, foliar S concentrations at 3 and 6 WAP tended to decline with increasing GRHB in substrates not amended with micronutrients, while remaining similar across GRHB rates among plants amended with micronutrients. All geraniums were near or above recommended foliar S concentrations throughout the experiment. Foliar micronutrient (B, Cu, Fe, Mn, and Zn) concentrations were, in nearly every case, higher in substrates amended with micronutrients compared to those not amended. Substrates amended with GRHB and micronutrients had higher foliar micronutrient concentrations than the NPK-control (except for foliar Fe and Zn at 30% GRHB). Previous research has shown that GRHB amended at rates up to 10% did not provide sufficient micronutrients to support crop growth in a soilless substrate (Altland and Locke 2013b). These data show that rates up to 30% still do not provide sufficient micronutrients to support crop growth. While micronutrient elements may be present in the GRHB material, they are not released in a form to become sufficiently available for plant uptake.

Experiment 2

Although not compared statistically, substrate pH response to GRHB rate followed a similar trend in geranium and tomato (Table 4). At 3 WAP within both species, pH was similar among substrates with 0–10% GRHB, and increased with rates of 15–20% GRHB. Only the 15 and 20% GRHB treatments had higher pH than the control substrate. By 5 WAP, substrate pH responded quadratically in both species to increasing GRHB amendment among containers fertilized with AN. Substrate pH declined from 0 to 10% GRHB, then increased thereafter. A similar quadratic response was observed in Experiment 1. The quadratic rate response is likely the result of the potential acidity of AN fertilizer along with the neutralizing effect from GRHB. The commercial fertilizer formulation used in the NPK-controls has a potential acidity of 200 kg/ton according to the manufacturer, while AN has a potential acidity of 591 kg/ton. The stronger acidifying effect of the AN fertilizer could have overwhelmed the neutralizing effect from lower rates of GRHB (Altland and Locke 2013b), while the neutralizing effect of higher GRHB rates ultimately increased substrate pH. Bi and Evans (2009) reported that pH in a peat moss-based substrate also increased quadratically with pulp mill ash amendment from 0 to 50% (v/v).

Table 4. Substrate pH and electrical conductivity in geranium (Pelargonium × hortorum "Maverick Red") and tomato (*Solanum lycopersicum* "Megabite") grown with 0–20% amendment of gasified rice hull biochar (GRHB) and fertilized with ammonium nitrate (AN), along with a control group fertilized with a complete water-soluble fertilizer (20–10–20) with all macronutrients and micronutrients.

					Electrical conductivity	
			Substrate pH		3 WAP	5 WAP
Crop	GRHB (%)	Fertilizer	3 WAP	5 WAP	mS cm^{-1}	
Geranium	0	20–10–20	6.50	6.41	0.99	0.76
	0	AN	6.47	6.52	1.38	2.20
	5	AN	6.46	6.28	1.35	1.05
	10	AN	6.59	6.25	1.90	0.91
	15	AN	6.74	6.37	2.06	0.93
	20	AN	6.90	6.47	2.36	1.09
	Rate response[z]		L***Q*	Q**	L***	L***Q***
	LSD$_{0.05}$[y]		0.13	0.19	0.27	0.27
Tomato	0	20–10-20	6.53	6.49	0.48	0.44
	0	AN	6.52	6.62	1.30	2.21
	5	AN	6.45	6.16	1.10	0.73
	10	AN	6.56	6.28	1.17	0.57
	15	AN	6.69	6.35	1.58	0.52
	20	AN	6.89	6.45	1.84	0.67
	Rate response		L***Q***	Q***	L***Q***	L***Q***
	LSD$_{0.05}$		0.12	0.18	0.27	0.13

[z]Indicates a significant linear (L) or quadratic (Q) rate response to GRHB rate, where *, **, or *** represents p-values of 0.05, 0.01, or 0.001, respectively.
[y]Least significant difference within a column, where $\alpha = 0.05$.

Substrate EC was affected by rate among both species at 3 and 5 WAP (Table 4). At 3 WAP, substrate EC increased linearly from 1.4 to 2.4 mS cm^{-1} with increasing GRHB among geranium, similar to Experiment 1. Substrate EC was slightly lower among tomato plants, with EC increasing from 1.3 to 1.8 mS cm^{-1} in GRHB-amended substrates. With both crops, EC of GRHB-amended substrates was higher than that of NPK-controls. By 5 WAP, EC was highest in substrates with 0% GRHB fertilized with AN in both crops. As will be discussed later, plants with 0% GRHB fertilized with AN were the smallest among both species. Higher substrate EC among this treatment is likely a result of the plants' small size and thus reduced capacity for water and nutrient uptake from the substrate. Substrate EC responded quadratically to increasing GRHB amendment in both crops. Substrate EC declined in substrates with 0% to 15% GRHB (Table 5), and increased with 20% GRHB. Others have shown increasing EC with increasing ash or biochar levels in peatmoss substrates (Bi and Evans 2009; Vaughn et al. 2013).

Leachate NO_3^- concentrations were highest in both crops and collection dates from containers fertilized with AN and amended with 0% GRHB (Table 6). Orthogonal contrast analysis indicated that NO_3^- concentration decreased linearly or quadratically with increasing GRHB amendment in both crops and collection dates, although rates from 5 to 20% GRHB were similar according to LSD values (with the exception of 5% GRHB in geranium 5 WAP). Similar to Experiment 1, leachate NO_3^- concentrations were negatively correlated to SDW ($R = -0.8838$, $n = 72$), suggesting NO_3^- remaining in the substrate solution was primarily a function of plant size and the plants' capacity to remove NO_3^- from the substrate. In both crops, leachate PO_4^{2-} concentration increased with increasing GRHB rate at 3 WAP. Phosphate levels in control plants were similar to the 5 and 10% GRHB amendment rate but lower than the 15 and 20% amendment rate in both crops. By 5 WAP, leachate PO_4^{2-} concentrations among geranium had a quadratic response to GRHB amendment where levels were moderately high at 0% GRHB, 0 mg L^{-1} from 5 to 10% GRHB, and moderately high again at 15 and 20% GRHB. It is unclear how containers with 0% GRHB had any PO_4^{2-} in leachates, as these containers had no source of P fertilizer. The absence of PO_4^{2-} in leachates of containers containing 5 and 10% GRHB

Table 5. Shoot and root dry weights of geranium (Pelargonium × hortorum "Maverick Red") and tomato (*Solanum lycopersicum* "Megabite") after 3 or 5 weeks of growth in a substrate amended with 0–20% gasified rice hull biochar and fertilized with ammonium nitrate (AN), along with a control group fertilized with a complete water-soluble fertilizer (20–10–20) with all macronutrients and micronutrients.

			Geranium		Tomato	
Weeks after potting	GRHB (%)	Fertilizer	Shoots	Roots	Shoots	Roots
			g			
3	0	20–10-20	1.20	0.15	1.41	0.30
	0	AN	0.56	0.11	0.20	0.07
	5	AN	1.15	0.18	1.50	0.31
	10	AN	1.25	0.15	1.63	0.34
	15	AN	1.24	0.18	1.56	0.32
	20	AN	1.18	0.17	1.45	0.30
	Rate response[z]		$L^{**}Q^{**}$	NS	$L^{***}Q^{***}$	$L^{***}Q^{***}$
	$LSD_{0.05}$[y]		0.35	NS	0.23	0.07
5	0	20–10-20	5.27	0.43	5.97	0.95
	0	AN	0.89	0.19	0.16	0.04
	5	AN	4.59	0.49	5.51	0.79
	10	AN	5.09	0.43	6.69	0.98
	15	AN	5.04	0.50	6.93	1.04
	20	AN	4.76	0.47	6.89	1.03
	Rate response		$L^{***}Q^{***}$	$L^{***}Q^{***}$	$L^{***}Q^{***}$	$L^{***}Q^{***}$
	$LSD_{0.05}$		0.50	0.09	0.64	0.13

[z]Indicates a significant linear (L) or quadratic (Q) rate response to GRHB rate, where *, **, or *** represents p-values of 0.05, 0.01, or 0.001, respectively.
[y]Least significant difference within a column, where $\alpha = 0.05$.

Table 6. Nutrient concentrations in leachates of geranium (Pelargonium × hortorum "Maverick Red") and tomato (*Solanum lycopersicum* "Megabite") at 3 and 6 weeks after potting (WAP), growing in substrates amended with 0–20% gasified rice hull biochar and fertilized with ammonium nitrate (AN), along with a control group fertilized with a complete water-soluble fertilizer (20–10–20) with all macronutrients and micronutrients.

			Geranium			Tomato		
Weeks after potting	GRHB (%)	Fertilizer	Nitrate	Phosphate	Potassium	Nitrate	Phosphate	Potassium
			$mg\ L^{-1}$					
3	0	20–10–20	193.7	107.6	32.1	54.2	72.5	8.5
	0	AN	330.3	22.7	7.2	314.3	48.0	11.5
	5	AN	120.8	76.8	29.2	66.4	73.6	13.7
	10	AN	100.3	98.4	94.4	49.6	78.7	32.4
	15	AN	105.0	135.8	163.1	71.6	106.1	98.5
	20	AN	154.7	179.8	229.9	53.0	140.7	176.2
	Rate responsez		$L^{***}Q^{***}$	L^{***}	$L^{***}Q^{***}$	$L^{***}Q^{***}$	L^{***}	$L^{***}Q^{***}$
	$LSD_{0.05}$[y]		55.4	19.3	18.9	35.0	20.4	20.4
5	0	20–10-20	19.0	50.2	4.5	7.5	14.6	0.8
	0	AN	581.8	29.8	3.5	600.1	15.0	5.4
	5	AN	132.4	0.0	5.0	36.0	0.0	0.0
	10	AN	49.9	0.0	5.7	8.9	0.0	0.8
	15	AN	39.1	37.9	8.5	12.8	0.0	1.7
	20	AN	26.1	40.1	10.9	27.7	30.1	8.3
	Rate response		$L^{***}Q^{***}$	$L^{*}Q^{**}$	L^{**}	$L^{***}Q^{***}$	Q^{**}	$L^{*}Q^{***}$
	LSD 0.05		26.6	25.1	5.1	30.7	19.3	2.9

[z]Indicates a significant linear (L) or quadratic (Q) rate response to GRHB rate, where *, **, or *** represents p-values of 0.05, 0.01, or 0.001, respectively.
[y]Least significant difference within a column, where $\alpha = 0.05$.

suggests that GRHB, the sole source of P in these containers, was insufficient to meet the needs of the crops for the 5-week production cycle. Leachate K levels increased linearly and quadratically with increasing GRHB amendment in geranium and tomato at 3 WAP. By 5 WAP, leachate K levels were substantially lower in GRHB treatments as plants utilized the K and no additional K was supplied via fertilizer.

Geranium and tomato had the lowest shoot mass when amended with 0% GRHB and fertilized with AN throughout the experiment (Table 5). This was not surprising, considering these plants had no source of available P or K. In both species, SDW responded linearly and quadratically to increasing GRHB rate, although rates from 5 to 20% were similar according to LSD values. At 3 WAP, plants amended with 5 to 20% GRHB were similar in size to NPK-control plants. By 6 WAP, geranium shoot mass in plants amended with 5 to 15% GRHB were similar to NPK-controls, while those fertilized with 20% GRHB were smaller than NPK-control plants. Among tomato plants, those fertilized with 5% GRHB were similar in size to NPK-control plants, while those amended with 10–20% GRHB had greater shoot mass than NPK-controls.

Geranium root mass was not affected by treatment at 3 WAP (Table 5). Geranium root mass 5 WAP was lowest among plants fertilized with AN and amended with 0% GRHB, but similar among all other treatments. Tomato roots were smallest among plants fertilized with AN and those amended with 0% GRHB at 3 and 5 WAP, while control and GRHB-amended plants all had similar root mass.

All foliar nutrients were affected by treatment 3 WAP. Foliar P and K in geranium fertilized with AN and amended with 0% GRHB were lower than NPK-control plants and lower than recommended minimum concentrations (Table 7). Foliar Ca and Mg concentrations were lower in GRHB-amended geranium compared to NPK-controls, but within the recommended range. All GRHB-amended geraniums had lower Fe and higher Mn levels than NPK-control plants. Iron and Mn are antagonistic in competition for absorption and translocation in plants (Mills and Jones 1996). Excessively high Mn from GRHB might have suppressed Fe uptake and deposition in geranium leaf tissue. By 5 WAP, geraniums amended with 0–10% GRHB had lower foliar P and K concentrations than the recommended minimums (Krug, Whipker, and McCall 2010). This is similar to previous research showing that plants amended with 10% GRHB have less than recommended foliar P and K values after 5 or 6 weeks of production (Locke, Altland, and Ford 2013). Foliar Ca and Mg levels in GRHB-amended plants were generally similar to NPK-controls. Foliar Fe levels remained lower than NPK-control plants and were suppressed below the recommended minimum concentration, while foliar Mn remained excessively high (Table 7).

Similar to geranium, tomato foliar P and K concentrations in plants fertilized with AN and those amended with 0% GRHB were lower than those in the NPK-control plants and the recommended minimum concentrations for leaf tissue. Foliar Ca and Mg concentrations decreased with increasing GRHB amendment, and plants with 5% GRHB or greater had lower Ca and Mg concentrations than NPK-control plants. Unlike geranium, tomato foliage 3 WAP had similar foliar Fe concentrations across all treatments, although foliar Mn was excessively high as it was for geranium. By 5 WAP, tomato plants fertilized with AN and those amended with 0 or 5% GRHB had lower foliar P and K than NPK-control tomatoes and the recommended minimums (Mills and Jones 1996). Foliar Ca, Mg, and Fe decreased with increasing GRHB amendment, with tomatoes amended with 15 or 20% GRHB having lower foliar Ca and Fe than NPK-control plants and recommended minimum tissue levels.

The objective of this research was to determine if higher rates of GRHB (>10%) would provide sufficient nutrients, with an emphasis on P and K, for production of crops in peat moss substrates, as well as any other positive or negative effects on plant performance. Addition of GRHB up to 30% in Experiment 1 affected physical properties of the peat moss-based substrate used in this experiment, generally improving water relations by increasing CC and decreasing UAW. Changes in physical properties from GRHB amendment might have a subtle effect on watering practices, but are not likely to be horticulturally significant. Experiment 1 established that regardless of rate, GRHB did not provide a sufficient source of micronutrients to support geranium crop growth in a peat moss substrate. This was especially evident in foliar concentrations of B, Fe, and Zn (Table 3). Because of this, we will hereafter only refer to plants grown in substrates amended with a micronutrient source in addition to GRHB.

Table 7. Foliar nutrient concentrations in geranium (Pelargonium × hortorum "Maverick Red") and tomato (*Solanum lycopersicum* "Megabite") at 3 and 5 weeks after potting (WAP) grown in substrates amended with 0–20% gasified rice hull biochar (GRHB) and fertilized with ammonium nitrate (AN), along with a control group fertilized with a complete water-soluble fertilizer (20–10–20) with all macronutrients and micronutrients.

Crop	WAP	GRHB (%)	Fertilizer	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
				(%)					mg kg^{-1}				
Geranium	3	0	20–10–20	0.63	3.49	1.21	0.91	0.34	25.2	2.6	148.5	111.4	34.6
		0	AN	0.10	0.70	0.87	0.62	0.29	43.7	9.4	76.0	572.7	53.4
		5	AN	0.36	4.03	1.09	0.72	0.35	35.4	9.4	93.0	545.7	62.9
		10	AN	0.52	4.63	1.06	0.72	0.39	37.8	7.8	95.9	489.7	52.1
		15	AN	0.59	4.99	0.96	0.68	0.35	35.2	7.6	74.2	482.1	55.7
		20	AN	0.61	5.24	0.80	0.61	0.34	33.0	7.1	71.3	467.5	50.9
			Rate response[z]	L***Q***	L***Q***	Q***	Q***	L*Q***	L**	L***	NS	L*	NS
			$LSD_{0.05}$[y]	0.07	0.48	0.13	0.09	0.04	6.1	1.0	34.4	101.1	10.5
	5	0	20–10-20	0.52	2.92	1.07	0.75	0.24	26.8	2.1	114.2	91.4	28.8
		0	AN	0.08	0.71	1.09	0.82	0.28	48.9	12.0	59.1	739.2	68.1
		5	AN	0.15	1.61	0.88	0.59	0.23	33.7	8.0	57.6	560.4	47.0
		10	AN	0.29	3.04	1.00	0.69	0.27	33.5	7.8	57.2	741.8	55.2
		15	AN	0.42	4.10	0.97	0.66	0.27	31.8	8.0	51.5	690.3	47.6
		20	AN	0.50	4.96	0.99	0.69	0.28	36.3	7.5	55.4	781.4	53.6
			Rate response	L***	L***	Q*	L*Q***	NS	L***Q***	L***Q***	NS	L*Q*	L**Q***
			$LSD_{0.05}$	0.04	0.37	0.11	0.07	0.03	3.5	1.4	19.5	93.5	8.1
			Recommended minimum[x]	0.3	2.5	0.8	0.2	0.18	35	5	70	110	36
Tomato	3	0	20–10–20	0.77	3.22	1.62	1.31	1.34	27.7	3.9	102.9	75.7	43.3
		0	AN	0.17	1.48	1.77	1.72	0.60	42.8	32.4	145.1	483.7	174.5
		5	AN	0.38	4.04	1.48	1.18	1.25	48.1	19.0	109.1	291.6	86.9
		10	AN	0.63	5.42	1.26	1.02	1.42	40.1	15.8	92.8	291.7	87.2
		15	AN	0.98	6.28	1.24	1.07	1.39	38.7	17.2	243.1	330.6	98.4
		20	AN	1.15	6.47	1.20	1.05	1.31	35.5	14.9	110.8	326.0	101.5
			Rate response	L***	L***Q**	L***Q**	L***Q**	L***Q**	L***Q*	L***Q***	NS	L***Q***	L***Q***
			$LSD_{0.05}$	0.07	0.99	0.13	0.10	0.15	3.3	3.4	NS	37.3	11.8
	5	0	20–10–20	0.48	2.27	1.44	1.11	0.72	32.9	3.0	64.9	60.2	24.3
		0	AN	0.10	1.01	1.79	1.73	0.60	53.4	38.8	93.6	432.7	290.8
		5	AN	0.15	1.56	1.51	1.32	0.56	44.6	11.8	50.6	330.7	58.8
		10	AN	0.26	2.08	1.41	1.09	0.85	48.6	10.6	56.4	354.7	42.3
		15	AN	0.42	2.67	1.21	0.92	0.79	39.1	10.5	41.5	363.3	42.2
		20	AN	0.63	3.97	1.19	0.93	0.88	40.8	10.3	45.7	418.3	59.0
			Rate response	L***Q***	L***Q*	L***Q*	L***Q***	L***	L***	L***Q***	L***Q**	Q***	L***Q***
			$LSD_{0.05}$	0.05	0.46	0.15	0.13	0.12	4.7	2.0	17.6	44.9	24.8
			Recommended minimum[w]	0.31	3.52	1.6	0.36	na	45	6	84	55	20

[z]Indicates a significant linear (L) or quadratic (Q) rate response to GRHB rate, where *, **, or *** represents p-values of 0.05, 0.01, or 0.001, respectively.
[y]Least significant difference within a column, where $\alpha = 0.05$.
[x]Krug, Whipker, and McCall 2010. Geranium leaf tissue nutrient sufficiency ranges by chronological age. Journal of Plant Nutrition 33:339–350.
[w]Millsand Jones 1996. Plant analysis handbook II. MicroMacro Publishing. Athens, GA.

Previous research had shown that by 5 or 6 WAP, foliar concentration of P and K declined to suboptimal levels (Altland and Locke 2013b; Locke, Altland, and Ford 2013). In Experiment 1, geraniums were likewise below optimal levels for P and K by 6 WAP when amended with 10% GRHB. Amendment with 20 or 30% GRHB resulted in acceptable foliar P and K levels; however, these plants had reduced shoot mass. Experiment 2 was similar with geranium, in that those amended with 0–10% GRHB were below optimum levels of P and K, while those with higher concentrations of GRHB amendment were within the optimum range. The 15% GRHB amendment did not reduce shoot or root growth compared to the NPK-control, while 20% GRHB reduced shoot growth slightly but not root growth. Tomato foliar P and K levels were likewise below optimal levels by 5 WAP when grown

in substrates amended with 10% GRHB or less. Unlike geranium, however, levels of GRHB greater than 10% did not reduce tomato shoot or root growth. This may be due to tomato being more tolerant of high pH substrates compared to geranium. It might also reflect species differences in tolerance to high mineral nutrient concentrations from GRHB. These results suggest that higher rates of GRHB (15–20%) will provide sufficient P and K for production of greenhouse crops in soilless substrates over a 5- to 6-week production cycle. Some crops, including geranium, might respond negatively to these higher rates with reduced shoot or root growth, while other crops, such as tomato, may respond positively with increased growth. Commercially produced water-soluble fertilizers traditionally used in greenhouse crop production, similar to the NPK fertilizer used in this experiment, can be formulated with virtually any combination or ratio of nutrients, as well as provide flexibility in the potential acidity. The drawback of biochars and other agricultural byproducts is that while they may provide some beneficial nutrient(s) or beneficial effect on substrate chemical or physical properties, they may also have additional effects (such as high pH or salts) that are difficult to remove or modify prior to inclusion in a potting substrate and may negatively affect crop growth.

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