Gasified Rice Hull Biochar Affects Nutrition and Growth of Horticultural Crops in Container Substrates[1]

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Abstract

This research was conducted to determine if gasified rice hull biochar (GRHB), inherently high in phosphorus and potassium content, could be used as an amendment to container substrates to eliminate the need for other phosphorus and potassium fertilizers. Geranium (*Pelargonium* x*hortorum* 'Maverick Red'), pansy *(Viola* x*wittrockiana* 'Mammoth Blue Deep Dazzle'), sunflower (*Helianthus annus* 'Pacino Gold'), zinnia (*Zinnia elegans* 'Oklahoma White'), and tomato (*Lycopersicon lycopersicum* 'Mega Bite') were grown in a standard commercial soilless substrate composed of sphagnum peat moss:perlite (85:15, by vol) and amended with 0, 5, or 10% GRHB (by vol). A group of plants labeled as NPK-fertilized controls were fertilized with 7.1 mM nitrogen (N), 0.7 mM phosphorus (P), and 1.4 mM potassium (K) derived from ammonium nitrate (NH_4NO_3) and potassium phosphate (K_2HPO_4). Other treatments received 0, 5, or 10% GRHB and fertilized with 7.1 mM N using NH_4NO_3. Gasified rice hull biochar had little effect on substrate pH over the course of the experiment. While pH was higher with 10% GRHB than NPK-fertilized controls by 6 weeks after potting (WAP), the difference was only 0.19 pH units. The GRHB used in this study provides a source of readily available phosphate and potassium when incorporated at 5 or 10%. While the five crops grown in this study were of similar size and lacked any signs of nutrient deficiency when amended with GRHB, foliar concentrations of P and K were low when their only source was from pre-incorporated GRHB.

Index words: bedding plants, phosphate, phosphorus, potassium, substrate pH.

Significance to the Nursery Industry

Nitrogen, phosphorus, and potassium are the primary nutrients applied to container crops. Phosphorus, in the form of phosphate, is becoming the most expensive fraction of complete fertilizers as its availability becomes more limiting. This research explores the use of a gasified rice hull biochar (GRHB) to provide phosphate and potassium to container crops over a short production cycle of 6 weeks. Using published sufficiency ranges for foliar P and K values, GRHB alone as an amendment at 5 to 10% by volume does not provide sufficient P or K for container crops. While plants growing in GRHB-amended substrates showed no visual symptoms of nutrient deficiency in terms of foliar color or reduced size, low foliar P and K values observed at 6 WAP in this study suggest that if production periods are longer than the six weeks, or plants grow larger relative to the pot size than those in this study, there may be reduced quality

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or size as the reduced P and K levels in the plant manifest into visual symptoms. This product has potential to replace P and K fertilizers dissolved in the irrigation stream, although additional work with higher rates for meeting plant needs over longer production periods is needed.

Introduction

Horticulture crops in soilless substrates require additions of N, P, and K fertilizer in higher quantities than other nutrients. Application and crop retention of N and P, more so than other nutrients, are scrutinized due to the adverse effects these two soluble and leachable nutrients have on ground and surface water systems.

In addition to adverse environmental effects of excess P released into surface and ground waters, there is a looming global shortage of P fertilizers. Phosphate fertilizer is a nonrenewable resource mined almost exclusively in a few countries, primarily Morocco, China, and the United States (4). It is predicted that phosphate reserves will be depleted in 50 to 100 years (4), during a time when phosphate demand will only increase for agricultural purposes to feed an increasing world population. As the price of phosphates increases over this time period, use of alternative phosphate sources will become prudent. Evans et al. (6) demonstrated a high P concentration in parboiled rice hulls, a byproduct of rice production that is already utilized as a component in many commercial greenhouse and nursery substrates. Gasified rice hull biochar (GRHB) has a similarly high P concentration, which is released in the reactive phosphate form and is available for plant uptake (unpublished data).

The influence of biochar on soilless substrates used in greenhouse and nursery container substrates has been studied little, and only a few citations tangentially related to greenhouse and nursery production in soilless substrates are available. Papers published thus far have addressed the effects of biochar on plant growth (8), microbial populations (7), calcium nutrition (13), substrate hydraulic properties (5), as well as chemical properties including pH, cation exchange capacity, and carbon to nitrogen ratio (5). None of these aforementioned papers addressed the influence of biochar on nitrates and phosphates in soilless substrates. Beck et al. (3) showed that amendment of an unspecified greenroof substrate with 7% biochar increased water retention and decreased total N and P, nitrate, phosphate, and organic carbon in runoff. More recently, Altland and Locke (1) demonstrated a temporary retention and release of nitrate and phosphate with a peat moss based substrate amended with 10% biochar. These papers did not address the influence of nitrate and phosphate retention on plant growth or fertility. Biochar elemental nutrient properties tend to reflect the properties of the original feedstock, only in higher concentration as a percentage of the carbon, hydrogen, and oxygen have been burned off during pyrolysis (11). Biochar used in the Beck et al. (3) and Altland and Locke (1) studies had low P and K concentrations, and thus showed some capacity to absorb and retain nitrates and phosphates. In contrast, Wells and Bush (15) reported that poultry litter ash, inherently high in P and K due to the poultry manure feedstock, provided sufficient P and K for production of several greenhouse crops. Considering the inherently high concentration of P and K in parboiled rice hulls (6), the objective of this research was to determine if a commercially available form of GRHB contains sufficient P and K to serve as the sole source of those nutrients in production of several greenhouse crops.

Table 1. Chemical properties of gasified rice hull biochar prior to substrate amendment. All analyses are expressed on a percent or concentration of oven dried biochar.

	Units	Value
pH		10.54
Carbon	(%)	17.68
Nitrogen		0.18
Phosphorus		0.30
Potassium		0.98
Calcium		0.35
Magnesium		0.15
Sulfur		0.03
Silicon		11.72
Boron	$mg \cdot kg^{-1}$	10.36
Copper		8.42
Iron		197.3
Manganese		541.0
Molybdenum		ND[z]
Zinc		46.34

[z]Not detectable.

Materials and Methods

A commercially available form of GRHB (CharSil, Riceland Foods, Inc., Stuttgart, AR) was used as an amendment with particle size distribution and chemical properties shown in Tables 1 and 2. This form of biochar is generated by passing rice hulls through a gasifier at 815 to 871C (1500 to 1600F) under substoichiometric conditions, with a residency time of 2 to 3 seconds. Particle size distribution was determined by passing approximately 45 g (16 oz) oven dried [55C (131F)] GRHB through 2.8, 2.0,1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm (0.75, 0.5, and 0.25 in, and nos. 5, 7, 10, 14, 18, 25, 35, 45, 60, 80, and 140) soil sieves. Particles ≤ 0.11 mm (no. 140 screen) were collected in a pan. Sieves and pan were shaken for 3 min with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}) (W.S. Tyler, Mentor, OH). Weight of GRHB collected by each sieve was measured. GRHB percent carbon (C) and nitrogen (N) were determined with a PerkinElmer Series II CHNS/O Analyzer (PerkinElmer Instruments, Shelton, CT). Other macronutrients and micronutrients were determined with a Thermo Iris Intrepid ICP-OES (Thermo Electron Corp., Waltham, MA).

Table 2. Particle size distribution of gasified rice hull biochar used as a greenhouse substrate amendment (n = 3).

Sieve size (mm)	Percent of sample	Standard deviation
< 0.106	25.8	1.34
0.106	20.2	0.86
0.18	13.9	0.11
0.25	15.5	0.33
0.35	12.1	0.51
0.5	9.5	0.96
0.71	1.9	0.29
1	0.5	0.07
1.4	0.5	0.11
2	0.1	0.06
2.8	0.0	0.01

Phosphate and K release. A laboratory experiment was conducted to determine the quantity and timing of phosphate and K release from GRHB. Four glass jars were each filled with 200 mL (6.8 oz) deionized water. A 5.4 g (0.19 oz) sample of GRHB was placed in a heat-sealed nylon (93 $g \cdot m^{-2}$, 100% nylon type 6.6 with 12 carbon atoms per repeating unit, Jo-Ann Fabrics, Hudson, OH) pouch. A single GRHB-filled pouch was placed in each of the jars. Each day (Mon–Fri) for 25 days, a 15 mL (0.5 oz) sample of solution was removed from each jar and frozen until phosphate and K analysis could be performed. At the time of nutrient analysis, samples were thawed, filtered through GF/F binder-free borosilicate glass fiber filter paper (Whatman Ltd., Kent, UK) to remove particles greater than 0.7 µm (2.28×10^{-5} in). The filtrate was then poured into 5 mL (0.17 oz) autosampler vials, capped, and analyzed on an ICS 1600 (Ion Chromatography System, Dionex, Bannockburn, IL) for concentrations of phosphate, and K. On every fifth day, after the 15 mL (0.5 oz) sample was collected, 75 mL (2.5 oz) of deionized water was placed back into each jar to reestablish the 200 mL (6.8 oz) volume. Mass of phosphate and K in solution was determined over time, accounting for the change in volume each day as well as the phosphate and K removed with each 15 mL (0.5 oz) sample. Phosphate and K mass over time were fit to an exponential equation [$y = a(1 - e^{-bx})$] where the fitted parameter a = the mass at which the curve plateaus and b is a scaling factor. Curve fitting was done with SigmaPlot 12.0 (Systat Software Inc., San Jose, CA).

Plant culture. The experiment was conducted in a glasshouse on the campus of the University of Toledo, OH. Throughout the experiment, natural light was supplemented with paired 250w high pressure sodium and 400w mercury vapor lights when outside ambient light levels dropped below 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (1020 fc). Greenhouse heat and cool thermostat set points were 21 and 26C (70 and 79F), respectively.

A standard commercial soilless substrate composed of sphagnum peat moss:perlite (85:15, by vol) (BM-6, Berger Peat Moss, Saint-Modeste, Quebec, Canada) was selected as the base substrate for the study. The base substrate contained no incorporated N, P, or K fertilizers, but was pre-incorporated with a proprietary blend of micronutrient fertilizers. Seedling transplants were produced in 200- or 288-cell plug trays containing the BM-6 substrate and grown for two to four weeks prior to transplant. Crops grown included geranium, pansy, sunflower, zinnia, and tomato.

The BM-6 substrate was amended with 0, 5, or 10% GRHB (by vol). Quantities of GRHB and substrate were measured more precisely by first establishing the weight of 60 and 600 cm^3 (3.7 and 37 in^3) of GRHB and substrate, respectively, then weighing the amount of GRHB and substrate to obtain the desired volumetric ratios. Sunflower, zinnia and tomato were transplanted with three plugs per 10-cm (4 in) pot, while geranium and pansy were transplanted as a single plug per pot. Pots hereafter referred to as the NPK-fertilized controls were grown in 100% BM-6 substrate and fertilized with 7.1 mM N, 0.7 mM P, and 1.4 mM K derived from ammonium nitrate (NH_4NO_3) and potassium phosphate (K_2HPO_4). Other treatments labeled as 0, 5, or 10% GRHB were amended with GRHB accordingly and fertilized with 7.1 mM N using NH_4NO_3. Plugs were transplanted into treatment-amended substrates on December 8, 2011, and watered in with tap water. Fertigation began on December 9, 2011, and continued, except for tap water irrigation once a week, for the duration of the experiment. Fertigation and irrigation was done to minimize leaching throughout the experiment.

At 2, 4, and 6 WAP (weeks after potting), tomato, pansy, and geranium were subjected to the pour-through technique (17) in order to collect a sample of the substrate solution for measurement of pH and nutrient analysis. For the containers used in this study, 50 mL (1.7 oz) of deionized water was poured on the substrate surface and approximately 40 mL (1.4 oz) was leached from the pot, collected, and analyzed. Substrate solutions were immediately measured for pH then frozen until a nutrient analysis was performed. At the time of nutrient analysis, samples were thawed and analyzed with the ICS 1600 system previously described for concentrations of nitrate, ammonium, phosphate, and K.

Following pour-through analysis, leaf greenness was determined on all crops with a SPAD chlorophyll meter (Minolta-502 SPAD meter, Spectrum Technologies, Inc., Plainfield, IL) by taking a measurement on five leaves per pot and recording the mean. At 2, 4, and 6 WAP, seven leaves of recently matured foliage from one of the three plants in each pot (among sunflower, tomato, and zinnia) were harvested for foliar nutrient analysis, rinsed with deionized water, then oven dried at 55C (131F) for 3 d. Geranium and pansy were only harvested at 6 WAP because there was only a single plant per pot for these two species. Samples were ground in a mortar and pestle and prepared for analysis. Foliar P was determined with a Thermo Iris Intrepid ICP-OES (Thermo Electron Corp., Waltham, MA). Immediately after leaf tissue harvests, shoot dry weight (SDW) of each crop was determined for the same plant harvested for leaf tissue analysis by removing the shoot portion of the plant, oven drying at 55C (131F) for 3 d and weighing.

There were five single pot replications per crop per treatment arranged in a completely randomized design with crops randomized and arranged separately. Data were subjected to analysis of variance (ANOVA) and repeated measures ANOVA, when appropriate, using SAS 9.1 (SAS Systems, Inc, Carey, NC). Data were also subjected to regression analysis using orthogonal contrast statements to identify the presence of a linear rate response to GRHB rate. Means were separated using Fisher's protected least significant difference (LSD) test with the LSD value presented.

Results and Discussion

Phosphate and K release. Phosphate and K release from GRHB were best described with exponential functions (Fig. 1). Both nutrients reached maximum concentration in 4 to 5 days. The fitted parameter *a* for each function describes the concentration at which the curve plateaus, thus the maximum concentration in solution that would be expected from the GRHB sample. The 5.4 g (0.19 oz) sample of GRHB released 35.2 mg (0.0012 oz) phosphate and 50.1 mg (0.0018 oz) K in water solution. Over a five-day period, the volume of water in each jar was reduced daily as samples were collected for analysis, and subsequently refilled on the fifth day to the original 200 mL (6.8 oz) volume. The mass of both nutrients remained constant over time despite fluctuations in water volume, suggesting the phosphate and K is released with little or no capacity or reserve. From these release curves, the quantity of phosphate and K can be projected in soilless substrates.

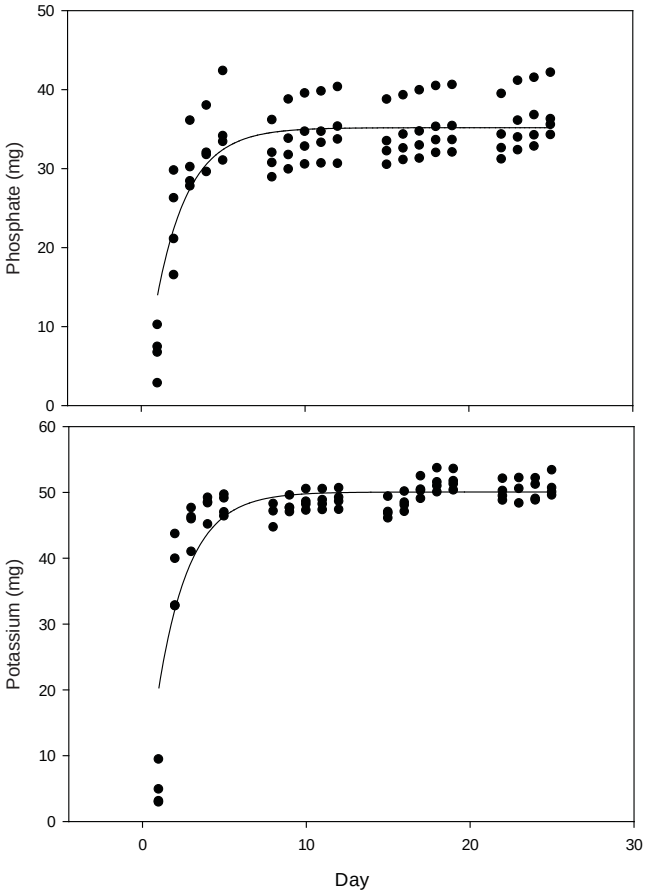

Fig. 1. Phosphate and potassium release from gasified rice hull biochar (GRHB) in a water solution. Glass jars were filled with 200 mL of deionized water and 5.4 g GRHB. Each day, a 15 mL sample was removed from each jar for analysis (n = 4). Curves for phosphate and potassium concentration over time were fit with exponential functions were phosphate = $35.2(1 - e^{-0.51x})$, $r^2 = 0.709$; and potassium = $50.06(1 - e^{-0.52x})$, $r^2 = 0.803$.

Substrate pH. Repeated measures analysis showed a significant treatment by time interaction in tomato substrate pH ($P = 0.0457$). Gasified rice hull biochar amendment rate had no effect on substrate pH at 2 WAP (Table 3). At 4 and 6 WAP, substrate pH increased linearly with increasing GRHB rate. Substrate pH response at latter stages in the experiment could have been caused by one of two factors. Others have reported the liming effect of biochar materials (2). Despite that GRHB used in this study had a pH of 10.54 (Table 1), it isn't likely that the observed pH response can be attributed to a liming effect from GRHB. Tomato containers amended with 5% GRHB had similar pH to NPK-fertilized controls throughout the experiment, and those fertilized with 10% GRHB had only slightly higher pH than NPK-fertilized controls at 6 WAP. An alternative possibility is that pH decline was caused by P deficiency. It has been shown that P-deficient plants respond by acidifying the rhizosphere with H^+ efflux from roots (9, 12). Considering the pH of containers with 0% GRBH (fertilized with NH_4NO_3 only) were similar to other containers at 2 WAP and declined further throughout the experiment, it is more likely the pH effect in this experiment resulted from the aforementioned P-deficiency induced efflux of H^+, and not from a GRHB-induced liming effect.

Substrate pH in geranium changed over time ($P < 0.0001$), however, there was no treatment by time interaction ($P = 0.4661$). Geranium substrate pH averaged 6.3 across treatments at 2 WAP, but dropped to 6.15 by 4 WAP, and further to 5.87 by 6 WAP (Table 3). Although repeated measures analysis showed no treatment by time interaction, univariate analysis of variance at 6 WAP showed a significant rate response in substrate pH to GRHB rate. At 6 WAP, containers amended with 10% GRHB had higher pH than all other treatments. Similar to the pH response in tomato, either GRHB caused a liming-effect or higher P levels in substrates amended with 10% GRHB resulted in less pH decline over time. Taylor et al. (14) showed substrate pH declined when geraniums were grown under P deficiency.

There was a significant treatment by time interaction for substrate pH in pansy containers ($P = 0.0007$). Substrate pH was similar across treatments at 2 and 4 WAP, averaging 6.45 and 6.33, respectively. By 6 WAP, substrate pH declined

Table 3. Substrate pH in tomato (*Lycopersicon lycopersicum*'Mega Bite'), geranium (*Pelargonium* x*hortorum* 'Maverick Red'), and pansy (*Viola* x*wittrockiana* 'Mammoth Blue Deep Dazzle') grown in sphagnum peat:perlite (85:15, by vol) substrate amended with 0, 5 or 10% gasified rice hull biochar (GRHB) and fertilized with ammonium nitrate, or not amended and fertilized with a nutrient solution containing nitrogen, phosphorus, and potassium.

		Tomato			Geranium			Pansy		
Treatment	**Fertilizer applied**	**2 WAP[z]**	**4 WAP**	**6 WAP**	**2 WAP**	**4 WAP**	**6 WAP**	**2 WAP**	**4 WAP**	**6 WAP**
Control	$NH_4NO_3 + K_2HPO_4$	6.44	6.31	6.18	6.25	6.10	5.85	6.41	6.32	6.34
GRHB 0%	NH_4NO_3	6.39	6.15	5.87	6.26	6.12	5.81	6.51	6.31	6.03
GRHB 5%	NH_4NO_3	6.47	6.37	6.21	6.30	6.14	5.75	6.42	6.32	6.30
GRHB 10%	NH_4NO_3	6.55	6.48	6.37	6.38	6.25	6.05	6.48	6.35	6.41
Linear rate response[y]		NS	L*	L***	NS	NS	L**	NS	NS	L**
$LSD_{0.05}$[x]		NS	0.25	0.17	NS	NS	0.16	NS	NS	0.23

[z]WAP is weeks after potting.

[y]Indicates significant linear (L) or non-significant (NS) rate response, where * and *** are significant at the 0.05 and 0.001 level.

[x]$LSD_{0.05}$ is the least significant difference, as determined by the Fisher LSD test.

Table 4. Nitrate, phosphate, and potassium concentration of leachate from tomato (*Lycopersicon lycopersicum* 'Mega Bite'), geranium (*Pelargonium* x*hortorum* 'Maverick Red'), and pansy (*Viola* x*wittrockiana* 'Mammoth Blue Deep Dazzle') in 10-cm pots during a pour-through procedure. Pour-throughs occurred at 2, 4, and 6 weeks after potting (WAP).

			Nitrate			Phosphate			Potassium		
Crop	Treatment	Fertilizer applied	2 WAP[z]	4 WAP	6 WAP	2 WAP	4 WAP	6 WAP	2 WAP	4 WAP	6 WAP
			mg·L^{-1}								
Tomato	Control	$NH_4NO_3 + K_2HPO_4$	41.9	19.1	2.8	6.6	6.7	4.0	3.9	1.6	0.5
	GRHB 0%	NH_4NO_3	79.4	140.2	174.8	0.0	0.0	0.0	3.6	1.8	2.4
	GRHB 5%	NH_4NO_3	28.2	25.3	45.2	8.1	0.8	0.0	26.9	2.6	0.3
	GRHB 10%	NH_4NO_3	22.2	15.9	2.3	29.1	1.5	0.0	83.3	1.0	0.3
	Linear rate response[y]		L***	L***	L***	L***	L*	NS	L***	NS	L**
	$LSD_{0.05}$[x]		20.6	40.3	49.6	6.5	1.3	1.3	11.3	NS	1.3
Geranium	Control	$NH_4NO_3 + K_2HPO_4$	81.2	25.5	5.3	8.4	10.2	4.8	7.8	2.4	1.5
	GRHB 0%	NH_4NO_3	131.6	194.2	149.4	0.0	0.0	0.0	3.3	1.6	2.2
	GRHB 5%	NH_4NO_3	86.6	44.7	42.1	13.4	0.7	0.0	32.5	1.3	0.7
	GRHB 10%	NH_4NO_3	71.7	17.4	53.7	32.9	1.6	0.4	72.3	4.5	1.2
	Linear rate response		L***	L***	L*	L***	NS	NS	L***	L*	L*
	$LSD_{0.05}$		34.1	21.2	80.2	8.4	2.7	1.7	18.2	2.7	0.9
Pansy	Control	$NH_4NO_3 + K_2HPO_4$	80.7	98.1	13.4	9.1	14.0	5.4	9.7	4.1	1.1
	GRHB 0%	NH_4NO_3	74.5	172.9	143.1	0.0	0.0	0.0	3.4	1.3	0.9
	GRHB 5%	NH_4NO_3	93.2	128.9	71.6	15.2	0.9	0.3	46.1	4.0	0.2
	GRHB 10%	NH_4NO_3	91.9	78.9	19.6	42.4	6.5	0.2	104.5	25.6	0.5
	Linear rate response		NS	L**	L**	L***	L*	NS	L***	L***	NS
	$LSD_{0.05}$		NS	65.2	72.5	6.4	5.9	3.2	7.2	4.2	NS

[z]WAP is weeks after potting.

[y]Indicates significant linear (L) or non-significant (NS) rate response, where * and *** are significant at the 0.05 and 0.001 level.

[x]$LSD_{0.05}$ is the least significant difference, as determined by the Fisher LSD test.

most in containers fertilized with ammonium nitrate but not amended with GRHB. The lack of difference in substrate pH between NPK-fertilized controls and those receiving 5 or 10% GRHB suggests that the pH response in pansy containers is due to P deficiency in those containers not amended with GRHB and only receiving N in the fertilizer solution.

Pour-through nutrient concentration. Repeated measures analysis showed a significant interaction between treatment and time for nitrate, phosphate, and K concentrations in pour-throughs for all crops on which the pour-through was conducted ($P < 0.0191$). Pour-through nitrate concentrations decreased linearly with increasing GRHB rate with each crop and collection date, with the exception of pansy at 2 WAP (Table 4). The 5 and 10% GRHB rates had similar pour-through nitrate concentrations to control pots, while containers receiving no GRHB and only ammonium nitrate had significantly higher nitrate concentrations. Others have reported reduced nitrate uptake in P-deficient plants (10, 12). It has been speculated that P-deficiency affects proper functioning of phospholipids at root cell membranes, thus inhibiting regulation of nitrate efflux and influx and favoring efflux (10). Concomitant with decreased nitrate uptake is a shift in favor of cation uptake (12). Increased cation uptake by plant roots would necessitate greater H^+ efflux to maintain charge balance and thus further depress pH. This corroborates the observed decrease in substrate pH of tomato and pansy plants with 0% GRHB fertilized only with ammonium nitrate. Throughout the study, in all crops and at all dates, pour-through ammonium-N levels were inconsequential compared to nitrate-N (data not shown).

Pour-through phosphate concentrations from containers receiving no GRHB or phosphate fertilizer were not detectable throughout the study, as expected. At 2 WAP, pour-through phosphate increased linearly with increasing GRHB rate in each crop (Table 4). Containers amended with 10% GRHB had higher phosphate concentrations than NPK-fertilized control containers. At 4 WAP, phosphate concentration in pour-throughs increased linearly with increasing GRHB rate in tomato and pansy, although NPK-fertilized controls had higher phosphate concentrations than all other treatments in all crops. By 6 WAP, there was no response in pour-through phosphate concentrations across GRHB amendment rate as substrates amended with 0 to 10% GRHB yielded extremely low concentrations of phosphate. Pour-through events could have depleted phosphate concentrations in GRHB-amended containers, but it's not likely. In a water solution, 5.4 g (0.19 oz) of GRHB yielded 35.2 mg (0.0012 oz) phosphate (Fig. 1). Containers amended with 10% GRHB would have received 11.3 g (0.40 oz) of the product. Assuming the same rate of

dissolution in the substrate as we found in pure water, 11.3 g (0.40 oz) GRHB would have yielded 73.6 mg (0.0026 oz) phosphate in the substrate solution. The highest pour-through phosphate concentrations occurred in pansy at 2 WAP with 42.4 mg·liter^{-1} (ppm) phosphate, which considering the leachate volume [40 mL (1.4 oz)] would have removed 1.7 mg (6.0×10^{-5} oz) of phosphate from the container. These pansies would have accumulated approximately 18 mg (0.0006 oz) phosphate in the shoots by 6 WAP. Phosphate depletion in the substrates over time in GRHB-amended substrates is likely the result of plant uptake, and not loss of phosphate from pour-through events.

At 2 WAP, K pour-through concentration increased linearly with increasing GRHB levels in each of the three crops. Pour-throughs from substrates with 5 or 10% GRHB had significantly higher K concentration than NPK-fertilized control pots. By 4 WAP, pour-through K increased linearly with increasing GRHB rate in geranium and pansy, but did not respond among tomato plants. By 6 WAP, K decreased with increasing GRHB rate in tomato and geranium. Similar to phosphates, K loss from containers is more likely a function of plant uptake and less likely due to losses from pour-through events. In the laboratory analysis, 5.4 g (0.19 oz) of GRHB yielded 50.2 mg (0.0018 oz) water soluble K (Fig. 1). Assuming the GRHB in the container substrates yielded the same relative quantity of K, there would have been 105 mg (0.0037 oz) K in containers amended with 10% GRHB. The highest K concentration in pour-throughs occurred among pansy receiving 10% GRHB at 2 WAP with 104.5 mg·liter^{-1} (ppm) K (Table 4), which considering the leachate volume [40 mL (1.4 oz)] would have resulted in approximately 4 mg (0.00014 oz) of K loss from the pour-through event. Those same pansies would have accumulated approximately 60 mg (0.0021 oz) in the shoots by 6 WAP. Similar to phosphates, far more K was absorbed by plants than lost via pour-through events.

Foliar nutrition. Repeated measures analysis showed a significant treatment by time interaction for foliar P in each crop that was harvested multiple times ($P < 0.0001$). Foliar P concentration increased linearly with increasing GRHB amendment at all sampling dates for all crops (Table 5). Among sunflower, tomato, and zinnia, the 5 and 10% GRHB amendment rates were similar to NPK-fertilized controls at 2 WAP (with the exception of zinnia amended with 5% GRHB). By 4 or 6 WAP, all crops fertilized only with ammonium nitrate had lower foliar P than NPK-fertilized controls. According to recommendations by Whipker et al. (16), sunflower in all treatments and all dates had less than recommended foliar P (with the exception of 10% GRHB at 2 WAP), despite

Table 5. Foliar phosphorus and potassium concentration on dry weight basis, after sunflower (*Helianthus annus* 'Pacino Gold'), tomato (*Lycopersicon lycopersicum* 'Mega Bite'), zinnia (*Zinnia elegans* 'Oklahoma White'), geranium (*Pelargonium xhortorum* 'Maverick Red'), and pansy (*Viola xwittrockiana* 'Mammoth Blue Deep Dazzle') were grown in sphagnum peat:perlite (85:15, by vol) substrate amended with 0, 5 or 10% biochar and fertilized with 3.6 mM NH_4NO_3, or not amended and fertilized with a nutrient solution 3.6 mM NH_4NO_3 and 0.7 mM K_2HPO_4.

			Sunflower			Tomato			Zinnia			Geranium	Pansy
Nutrient	Treatment	Fertilizer applied	2 WAP[z]	4 WAP	6 WAP	2 WAP	4 WAP	6 WAP	2 WAP	4 WAP	6 WAP	6 WAP	6 WAP
			%										
Phosphorus	Control	NH_4NO_3 + K_2HPO_4	0.61	0.67	0.68	0.85	0.79	0.68	0.88	0.99	0.85	0.41	0.73
	GRHB 0%	NH_4NO_3	0.38	0.19	0.15	0.22	0.11	0.09	0.25	0.14	0.09	0.08	0.11
	GRHB 5%	NH_4NO_3	0.63	0.45	0.28	0.72	0.32	0.14	0.77	0.35	0.15	0.14	0.23
	GRHB 10%	NH_4NO_3	0.70	0.59	0.45	0.86	0.53	0.24	0.86	0.73	0.31	0.22	0.33
	Linear rate response[y]		L***	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***
	$LSD_{0.05}$[w]		0.04	0.05	0.07	0.15	0.05	0.04	0.08	0.06	0.08	0.03	0.07
	Recommended range			0.7–0.8[v]			0.31–0.46[u]			0.74[u]		0.33–0.51[t]	0.37–0.64[u]
Potassium	Control	NH_4NO_3 + K_2HPO_4	3.65	3.88	4.16	4.22	3.66	2.74	4.27	3.54	3.05	1.97	4.33
	GRHB 0%	NH_4NO_3	2.28	1.81	1.89	2.48	2.04	2.34	2.16	1.71	1.79	1.55	2.55
	GRHB 5%	NH_4NO_3	4.72	3.79	2.53	4.77	2.58	1.63	5.60	3.12	1.56	1.41	2.69
	GRHB 10%	NH_4NO_3	5.21	4.82	3.68	5.54	4.07	2.07	6.70	5.23	2.33	2.14	3.37
	Linear rate response		L***	L***	L***	L***	L***	L**	L***	L***	L**	L**	L*
	$LSD_{0.05}$		0.26	0.33	0.45	0.79	0.46	0.15	0.56	0.49	0.30	0.35	0.66
	Recommended range			5.4–6.3			3.5–5.1			3.3		3.2–3.4	2.4–2.9

[z]WAP is weeks after potting.

[y]Indicates significant linear (L) or non-significant (NS) rate response, where * and *** are significant at the 0.05 and 0.001 level.

[x]$LSD_{0.05}$ is the least significant difference, as determined by the Fisher LSD test.

[w]Least significant value as determined by Fisher's test when $\alpha = 0.05$.

[v]Whipker, B.E., S. Dasoju, and I. McCall. 1998. Guide to successful pot sunflower production. North Carolina Coop. Ext. Serv. Hort. Information Leaflet 562.

[u]Mills, H.A. and J.B. Jones. 1996. Plant Analysis Handbook II. MicroMacro Publishing. Athens, GA.

[t]Krug, B.A., B.E. Whipker, and I. McCall. 2010. Geranium leaf tissue nutrient sufficiency ranges by chronological age. J. Plant Nutr. 33:339–350.

Table 6. Shoot dry weight of sunflower (*Helianthus annus* 'Pacino Gold'), tomato (*Lycopersicon lycopersicum* 'Mega Bite'), zinnia (*Zinnia elegans* 'Oklahoma White'), geranium (*Pelargonium* x*hortorum* 'Maverick Red'), and pansy (*Viola* x*wittrockiana* 'Mammoth Blue Deep Dazzle') grown in sphagnum peat:perlite (85:15, by vol) substrate amended with 0, 5 or 10% gasified rice hull biochar (GRHB) and fertilized with ammonium nitrate, or not amended and fertilized with a nutrient solution containing N, P, and K.

		Sunflower			Tomato			Zinnia			Geranium	Pansy
Treatment	Fertilizer applied	2 WAP[z]	4 WAP	6 WAP	2 WAP	4 WAP	6 WAP	2 WAP	4 WAP	6 WAP	6 WAP	6 WAP
Control	$NH_4NO_3 + K_2HPO_4$	0.28	0.66	1.29	0.18	0.55	1.93	0.19	0.69	1.61	4.21	1.68
GRHB 0%	NH_4NO_3	0.27	0.52	0.66	0.12	0.17	0.14	0.17	0.35	0.38	0.58	0.38
GRHB 5%	NH_4NO_3	0.30	0.72	1.66	0.22	0.58	1.34	0.24	0.76	1.30	4.19	1.43
GRHB 10%	NH_4NO_3	0.31	0.73	1.46	0.17	0.85	1.62	0.19	0.80	1.64	4.43	1.77
Linear rate response[y]		NS	L***	L***	NS	L***	L***	NS	L***	L***	L***	L***
GRHB 10%	NH_4NO_3	0.31	0.73	1.46	0.17	0.85	1.62	0.19	0.80	1.64	4.43	1.77
$LSD_{0.05}$[x]		NS	0.11	0.26	.07	0.12	0.32	NS	0.17	0.34	0.75	0.38

[z]WAP is weeks after potting.

[y]Indicates significant linear (L) or non-significant (NS) rate response, where * and *** are significant at the 0.05 and 0.001 level. [x]$LSD_{0.05}$ is the least significant difference, as determined by the Fisher LSD test.

[x]$LSD_{0.05}$ is the least significant difference, as determined by the Fisher LSD test.

that all sunflowers in this study (with the exception of those receiving 0% GRHB and only ammonium nitrate) appeared healthy and vigorous. It's possible that the cultivar used in this study requires lower foliar P concentration for healthy growth than those used to form the recommendation by Whipker et al. (16). Tomatoes in the NPK fertilized controls had sufficient foliar P throughout the experiment. Tomatoes receiving 5 and 10% GRHB at 2 and 4 WAP had sufficient foliar P, but less than desired levels by 6 WAP. A similar trend was observed in zinnia where NPK-fertilized controls had sufficient foliar P throughout the study while zinnia receiving 5 or 10% GRHB dropped below recommended levels by 4 WAP. Geranium and pansy had sufficient foliar P in NPK-fertilized controls when harvested 6 WAP at the conclusion of the experiment, but less than recommended levels in all other treatments.

Repeated measures analysis showed a significant interaction between time and treatment for foliar K in each of the three crops that were harvested multiple times ($P < 0.0001$). Foliar K increased linearly with increasing GRHB rate in all crops at all harvest dates (Table 5). Similar to foliar P, foliar K was initially high in plants amended with 5 or 10% GRHB. Among all crops harvested 2 WAP, all plants amended with GRHB had similar foliar K concentration to NPK-fertilized controls. However, by 6 WAP, foliar K concentrations in NPK-fertilized controls were higher than all other treatments in all crops with the exception of geranium.

Shoot dry weight did not respond to GRHB rate for any of the measured crops 2 WAP; however, SDW of all crops increased linearly with increasing GRHB rate thereafter. All crops at all dates amended with either 5 or 10% GRHB were similar to or larger than NPK-fertilized controls (except tomato with 5% GRHB at 6 WAP). Conversely, all crops with 0% GRHB fertilized with only ammonium nitrate were smaller than NPK-fertilized controls by 4 WAP. All crops with 0% GRHB fertilized with ammonium nitrate displayed, to varying degrees, classic symptoms of P deficiency including purple foliage, stunted leaves, and reduced plant growth. Foliar SPAD values were recorded for all crops; however, SPAD values were erratic across treatments and crops. Some crops responded to P deficiency with smaller darker green to purple foliage, which tended to cause increased SPAD values. For other crops, low foliar P concentration resulted in lower SPAD values. For these reasons, SPAD data were misleading and difficult to interpret, and thus were not included.

In summary, these data demonstrate that GRHB used in these studies, incorporated at 5 or 10% (v/v) had little effect on substrate pH over the course of the experiment. While pH was higher with 10% GRHB than NPK-fertilized controls at 6 WAP, the difference was only 0.19 pH units. The GRHB used in this study is a source of readily available phosphate and K when incorporated at 5 or 10%. While the five crops grown in this study were of similar size and lacked any signs of nutrient deficiency at 6 WAP, foliar concentrations of P and K were low when their only source was from pre-incorporated GRHB.

If the amount of available phosphate from GRHB in substrates is consistent with that released in a pure water system, there should be 36.8 and 73.6 mg (0.0013 and 0.0026 oz) phosphate in containers amended with 5 and 10% GRHB, respectively. Considering the final SDW (Table 6) and recommended foliar P concentrations (Table 5), sunflower, tomato, zinnia, geranium, and pansy should have required 36, 17, 33, 59, and 25 mg (0.0013, 0.0006, 0.0012, 0.0021, and 0.0009 oz) phosphate to supply P for the shoot portion of the plant. Therefore, the GRHB incorporated at 10% could have theoretically provided sufficient phosphate for all crops in this study. While no deficiency symptoms were observed in these crops, lower foliar P concentration in all crops amended with GRHB, and foliar P concentrations lower than NPK-fertilized controls by the conclusion of the study, suggests that phosphates from the GRHB were either not available at the same level they were measured in a pure water system, or plant roots did not have access to phosphates that would presumably be distributed uniformly throughout the container substrate solution. A similar argument could be made for K. According to minimum sufficiency levels for foliar K (Table 5) and SDW of plants by the conclusion of the study (Table 6), sunflower, tomato, zinnia, geranium, and pansy would require 79, 57, 54, 142, and 43 mg (0.0028, 0.0020, 0.0019, 0.0050, and 0.0015 oz) K, respectively, for their shoots. Gasified rice hull biochar at 10% would have provided 105 mg

(0.0037 oz) K, which would be sufficient to meet the needs of all crops with the exception of geranium.

The objective of this research was to determine if a commercially available form of GRHB (Charsil) contains sufficient P and K to serve as the sole source of those two nutrients in production of container crops. Towards this objective, GRHB-amended substrates were compared to a common industry practice of continuous fertilization with a commercial water-soluble fertilizer. Throughout the study, all plants fertilized with the NPK-control treatment had sufficient foliar P according to published sufficiency ranges (Table 5). Among the five crops fertilized with NPK-control treatments, only pansy had sufficient foliar K levels by 6 WAP. Nonetheless, NPK-fertilized controls had higher foliar K than plants in GRHB-amended substrates, with the exception of geranium. Using foliar P and K values in our designated 'industry standard' NPK-fertilized controls or published sufficiency ranges as a guide, GRHB alone as an amendment at 5 to 10% by volume does not provide sufficient P or K for container crops. While plants growing in GRHB-amended substrates showed no visual symptoms of nutrient deficiency in terms of foliar color or reduced size, low foliar P and K values observed at 6 WAP in this study suggest that if production periods are longer than the six weeks, or plants grow larger relative to the pot size than those in this study, there may be reduced quality or size as the reduced P and K levels in the plant manifest into visual symptoms. This product has potential to replace P and K fertilizers dissolved in the irrigation stream, although additional work with higher rates for meeting plant needs over longer production periods is warranted.

It should not be assumed these results will apply to other forms of biochar. Biochar nutrient properties tend to reflect the properties of the original feedstock (11) and thus can vary greatly in their composition, properties, and influence on soil systems depending on the original feedstock and how it was pyrolyzed. The results in this study only reflect the properties of rice hulls gasified at 815 to 871C (1500 to 1600F) under substoichiometric conditions for 2 to 3 seconds. The GRHB generated in this manner, however, is commercially available in large quantities and thus could be used in commercial horticulture. The commercial form of GRHB used in this research (Charsil) is not marketed for horticulture as of this writing.

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