HortScience 60(11):2096–2103. 2025. https://doi.org/10.21273/HORTSCI18842-25

Evaluation of Different Biochar Sources as Potential Media Amendments for Container Plant Production of Native Plants

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Keywords. container production, *Epilobium canum*, growing medium, *Philadelphus lewisii*, *Spirea douglasii*

Abstract. **Biochar, an organic material produced by pyrolysis, is being explored as a sustainable alternative to horticultural-grade bark and peatmoss in growing media. In this study, biochars derived from the following four feedstocks were evaluated as partial replacements for peats: (1) dried dairy manure; (2) *Pinus ponderosa* sawdust; (3) ground wood waste; and (4) commercial nonfood biomass products. Media formulations containing concentrations of biochar of 0%, 5%, 10%, 15%, or 20% were combined with 70% aged bark and the remaining was filled with sphagnum peatmoss. Plants of three native shrub species, Douglas spirea (*Spirea douglasii*), mockorange (*Philadelphus lewisii*), and firechalice (*Epilobium canum* var. *garrettii*) were grown in these substrates for 3 months. To determine the effects of the media, at harvest, the shoot dry weights for all species were determined. Similarly, data regarding the heights of spirea and mockorange and the diameter of the canopy of firechalice plants were also measured. All substrate mixes exhibited acceptable physical properties, including air capacity, water-holding capacity, and total porosity. However, chemical analyses revealed that nutrient contents varied by biochar source, which could have influenced plant growth responses. Dairy manure biochar applied at more than 5% suppressed spirea and mockorange growth, likely because of excessive salt content. Ponderosa pine biochar generated shoot dry weights comparable to those of the control, but mockorange height declined by at least 17%. In contrast, biochar from ground wood waste and commercial biochar maintained plant size across most treatments, with the greatest shoot growth observed for spirea and firechalice in the 10% commercial treatment. Firechalice shoot dry weight was reduced in all ground wood waste treatments, whereas in both spirea and firechalice, an increase in shoot dry weight was observed only with the 10% commercial treatment amendment. Overall, commercial biochar demonstrated potential as a peatmoss substitute, while dried dairy manure, *Pinus ponderosa* sawdust, and ground wood waste biochars negatively affected at least one of the species assessed.**

Container plant production traditionally uses soilless media composed of horticultural-grade bark and sphagnum peatmoss. High costs and sustainability of peatmoss have driven the demand for alternative amendment components (Fascella et al. 2018; Guo et al. 2018; Kaudal et al. 2016; Vaughn et al. 2013). One of the possible replacements is biochar, a carbon-rich material produced by pyrolysis of biomass waste (Fascella et al. 2018). Pyrolysis involves thermal decomposition by heating the waste to higher than 250 °C (usually 450–600 °C) in the absence of oxygen (Prasad et al. 2018). The resulting biochar has significant potential for enhancing soil quality and promoting plant growth (Bedussi et al. 2015; Cantrell et al. 2012; Kaudal et al. 2016; Prasad et al. 2018). Some other benefits of biochars include its ability to improve cation exchange capacity as well as increase nutrient and water retention, lower bulk densities, immobilize heavy metals, and improve pH (Housley et al. 2015; Prasad et al. 2018; Uzoma et al. 2011; Vaughn et al. 2013).

Previous biochar trials have been focused on the application of biochars to soil instead of soilless media. Zwieten et al. (2010) found that applying papermill waste biochars to ferrosols improved the growth of soybean and radish. However, when it was applied to calcarosol soils, only the growth of soybean was improved, while biomass of wheat and radish decreased. Uzoma et al. (2011) reported yield increases of up to 150% in maize grown on sandy soil amended with dairy manure biochar. Asai et al. (2009) observed higher rice yields in phosphorus-deficient fields in Laos. Smider and Singh (2014) found that corn shoot biomass doubled in ferrosol but decreased in tenosol soils amended with tomato green waste biochar.

Studies of biochar use in peat-based and coir-based substrates have produced mixed results, with outcomes influenced by biochar type, incorporation rate, and plant species. Hardwood and wheat straw biochars improved tomato height and marigold growth (Vaughn et al. 2013), while olive mill waste biochar performed better than forest waste or hydrochar in tomato production (Fornes et al. 2017). Rice hull biochar enhanced nutrient retention and water availability, thus increasing kale biomass (Kim et al. 2017), and commercial biochars reduced nutrient leaching but lowered nitrogen (N) and phosphorus (P) availability, suggesting their use in seedling production (Prasad et al. 2017). Moderate additions of conifer wood biochar sustained rose growth and quality (Fascella et al. 2018), and poinsettia tolerated up to 80% biochar in peat mixes with minimal quality loss under proper fertigation (Guo et al. 2018). Therefore, it is essential to evaluate the physical and chemical properties of each biochar, as well as the responses of various plant species to their presence in the growth media, before its use by container plant growers.

This study investigated the effects of four distinct biochars on the plant growth of native shrubs (*Spiraea douglasii*, *Philadelphus lewisii*, and *Epilobium canum* var. *garrettii*) cultivated in bark–peat-based container media. The biochars evaluated were derived from dried dairy manure (DM), *Pinus ponderosa* sawdust (PP), a commercial nonfood biomass product (CP), and ground wood waste (GWW).

Materials and Methods

Biochar characterization. In this study, DM (University of Idaho dairy program, Mosco, ID, USA) and PP (local sawmill, Viola, ID, USA) were used in 2015, whereas a mixture of GWW remaining on the forest floor after timber harvest (Washington State University, Pullman, WA, USA) and CP (Cool Planet; Greenwood Village, CO, USA) were used in 2016. The DM and PP biochars were produced at the University of Idaho using a 100-mm diameter auger pyrolysis reactor (mobile in-house modified reactor; Advanced BioRefinery Inc., Quebec, Canada) operating at 480 to 500 °C with a feed rate of 20 $kg \cdot h^{-1}$ (Han et al. 2016). Pyrolysis vapors were condensed via a series of five tube-shell condensers, while noncondensable gases were combusted along with propane to heat the reactor. Biochar was collected following passage through a water-cooled jacketed auger.

Chemical analyses of three subsamples of each biochar were performed to determine concentrations of nitrate (NO_3-N), ammonium (NH_4-N), P, potassium (K), boron (B), sulfate sulfur (S), zinc (Zn), manganese (Mn), copper (Cu), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), and extractable chloride (Cl^-). Dry plant samples were ground in a mortar to a fine powder and analyzed to determine tissue mineral concentrations (Brookside Laboratories Inc., New Bremen, OH, USA). The total N content was determined using a combustion method and a Carlo Erba 1500 C/N analyzer (Thermo Fisher Scientific, Waltham, MA, USA) (Miller et al. 2013). Concentrations of other minerals were quantified following digestion with nitric acid and hydrogen peroxide in a closed Teflon vessel using a Mars Microwave (CEM, Matthews, NC, USA), and the analysis was conducted with a Thermo 6500 Duo ICP (Thermo Fisher Scientific) (Miller et al. 2013). Initial pH and electrical conductivity (EC) were measured using the saturated paste extraction method (Rhoades et al. 1989). The cation exchange capacity (CEC) was determined using the barium acetate method at the Analytical Sciences Laboratory of the University of Idaho.

Growing media. Five growing media were formulated for each biochar with a rate of 0%, 5%, 10%, 15%, or 20% biochar by volume, along with 70% aged bark and enough peatmoss to achieve a total volume of 100%. Additionally, all mixes were supplemented with Micromax micronutrient fertilizer (ICL, St. Louis, MO, USA) at a rate of 683 mg/L. Controlled-release fertilizer (Osmocote 15–9–12; Scotts Company LLC, Marysville, OH, USA) was incorporated at a medium rate of 4.54 kg into mixes containing PP and DM, whereas a higher rate of 6.58 kg was applied to mixes containing CP and GWW.

Ground lime was added to adjust the pH above 5, except in DM at 10% or higher because of the inherently high pH. The amount of lime added was dependent on the rates of biochar; therefore, it ranged from 60 g in 20% to 350 g in the control. The physical properties of the media, including air capacity, water-holding capacity, and total porosity, were evaluated in four subsamples of each mix following the methodology of Holstead (1983). In addition, chemical analyses (P, K, and Na) and CEC measurements were also conducted; however, the 2015 samples were collected following Osmocote (Scotts Company LLC) incorporation, which confounded the results.

Plant selection. Native deciduous shrubs were selected for this study. In 2015, Douglas spirea (*Spirea douglasii*) and syringa/mockorange (*Philadelphus lewisii*) plants were obtained as plugs from Plants of the Wild (Tekoa, WA, USA). In the trial of 2016, Douglas spirea and firechalice (*Epilobium canum* var. *garrettii*) were used, with firechalice plants propagated via tissue culture (Alosaimi et al. 2018). Moreover, rooted firechalice plantlets were acclimated in high-humidity chambers for 1 month before being transplanted into 10-cm pots with Sunshine Mix #1 (Sun Gro, Bellevue, WA, USA).

Plant growth experiments. In 2015, Douglas spirea and mockorange plants were pruned to a single stem so they had similar heights at the time of planting. In contrast, the plant materials used in 2016 were pruned 11 d after planting. All plants were transferred into 4-L pots containing experimental mixes. Initial EC measurements indicated salt toxicity in DM (rates of 10%–20%), for which they needed to be leached before planting. Leaching involved adding water to the top of the containers filled with the growing media and then allowing drainage. Specifically, 10% and 15% manure biochars were leached three times, whereas the 20% manure biochar was leached four times. The other mixes did not require leaching. After leaching, plants were allowed to acclimate for 10 d (DM and PP biochars), 13 d (GWW biochar), or 17 d (CP biochar). After the acclimation period, 20 plants per treatment were selected to ensure uniformity and subsequently arranged in a randomized complete block design within a modified pot-in-pot system at the University of Idaho Research Farm (Moscow, ID, USA). Each treatment consisted of five replicates for 10 treatments across four blocks involving two species, resulting in a total of 200 plants of each species per trial.

Plants were irrigated approximately three times weekly using a microemitter irrigation system with spray stakes (average volume of 235 mL per irrigation event) and received supplemental liquid fertilizer during both trials. During the 2015 trial, plants were fertilized approximately every 10 d (a total of four times) with supplemental liquid fertilizer (Miracle-Gro; Scotts Company LLC) containing 100 ppm N. Initially, a 24–8–16 fertilizer was used; however, because of increasing pH levels, an acidifying fertilizer (21–7–7) was used in the later applications. For the 2016 trial, a liquid fertilizer containing 150 ppm N (24–8–16) was applied approximately every 21 d (a total of four applications).

In 2015, the height of the plants was measured after 97 d of growth. In 2016, the height of spirea and canopy diameter of firechalice were measured 87 d after planting. Data regarding shoot dry weight were collected for both trials by cutting stems level with the medium surface. The cut shoots were dried at 40 to 50 °C for 10 to 20 d in a forced-air oven and then weighed to determine shoot dry weights.

Statistical analysis. Chemical properties of biochars were analyzed separately by year. Data normality was evaluated using the univariate procedure in SAS (SAS 2014; SAS Institute Inc., Cary, NC, USA). Variables such as NO_3-N, NH_4-N, P, K, and pH were analyzed using a lognormal distribution. Treatment effects were assessed using a general linear mixed model (PROC GLIMMIX; SAS Institute Inc.), with least squares means tested at a 5% significance level.

Key chemical properties in the growing media were analyzed separately by trial year (2015 and 2016) and tested for normality using the univariate procedure. The significance of the main effects of biochar type and concentration as well as the potential interaction between biochar type × concentration were determined using the GLIMMIX procedure (SAS Institute Inc.) with a lognormal distribution for P, K, and Na to adjust for skewness and a normal distribution for CEC. Significant differences in the main effects or interaction terms were assessed using the least square means. Media physical properties (aeration/air-holding capacity, water-holding capacity, and total porosity) for each trial were converted to proportions and then analyzed as described, but with a beta-normal distribution.

Plant growth metrics (height, dry weight, canopy diameter) by species within a trial date were initially averaged by block and then statistically analyzed to determine the effects of biochar type, concentration, and any interaction between biochar type × concentration using the general linear mixed model. Least squares mean at the 5% significance level were used to determine significant differences between means within each trial.

Results

Raw biochar, bark, or peatmoss characteristics. Variations in mineral content, pH, EC, and CEC were found among the different media components (Table 1). In DM, the levels of P, K, Ca, Mg, S, Na, and chloride (Cl) were significantly higher than those in any other media. The levels of P (6897 mg/kg), K (14,379 mg/kg) and Cl (11,956 mg/kg) in the DM were at least 71-fold greater than the levels in peatmoss. The CP contained the highest level of NO_3-N (10.6 mg/kg), which was approximately 4.6-times higher than that in either peat or bark. Additionally, CP contained significantly higher levels of P (228 mg/kg), K (5684 mg/kg), Na (8.4 meq/100 g), and Cl (562 g/kg) when compared with the other biochars except for DM. The pH values were variable and ranged from 4.2 in peatmoss to 10.4 in DM. The CECs of all biochars were substantially lower than that of peatmoss,

Received for publication 7 Jul 2025. Accepted for publication 5 Sep 2025.
Published online 8 Oct 2025.
We thank the Nursery Advisory Committee of the Idaho State Department of Agriculture for funding part of this research (grant NAC/ISDA 2015-3). We thank Richard Finch (Washington State University) for providing the GWW biochar. We thank Dr. William Price, Director of Statistical Programs (University of Idaho), for statistical assistance. This research was supported, in part, by the USDA National Institute of Food and Agriculture Hatch/Evans project IDA01545. We thank the Idaho Agricultural Experiment Station for supporting this research.
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Table 1. Average chemical properties in each media, including four biochars made from different sources (GWW, CP, DM, and PP) as well as sphagnum peatmoss and bark. Different letters within a row (chemical property) and within a year (2015 or 2016) indicate significant differences as determined by using least-squares means at the 5% level (n = 3 except for bark, with n = 2). Values without a letter indicate nonsignificant differences. All chemical properties except pH were adjusted to a lognormal distribution to address skewness.

		Media components					
		2015				2016	
Chemical properties		DM	PP	Peat	Bark	GWW	CP
NO_3-N		0.4	0.5	2.3	2.0	1.7	10.6
NH_4-N		8.3 b	0.8 c	131a	10.2 b	7.2 b	56.2 a
P		6897 a	36.6 b	42.2 b	61.4 b	107 b	228 a
K		14,379 a	397 c	29.5 d	1175 b	1725 b	5684 a
S		591 a	18.9 c	271 b	16.9 c	19.5 b	113 a
Cl^-	mg/kg	11,956 a	127 b	168 b	173 b	36.6 b	562 a
Zn		5.8 c	3.2 d	15.0 b	23.2 a	3.7 a	2.1 b
Fe		22.9 c	118 b	650 a	27.4 c	2.6	18.5
Mn		19.5 b	14.3 c	104 a	114 a	11.0 a	3.2 b
Cu		1.7	0.8	1.1	1.1	0.1	0.8
B		4.3 a	0.6 d	2.9 b	0.9 c	0.4 b	0.7 a
Ca		10.9 a	2.1 d	2.5 c	8.3 b	8.6 a	3.2 b
Mg	meq/100 g	4.6 a	0.6 d	1.0 c	2.8 b	0.6 b	2.9 a
Na		34.8 a	0.4 b	0.1 d	0.2 c	2.6 b	8.4 a
pH[i]		10.4 a	5.6 b	4.3 d	4.8 c	8.9 a	7.3 b
EC ($mS \cdot cm^{-1}$)	$mS \cdot cm^{-1}$	58.4 a	1.1 bc	1.6 b	0.7 c	3.3 b	4.6 a
CEC (cmol (+)/kg)	cmol(+)/kg	2.3 c	1.9 c	130 a	41.0 b	46.0 a	30.0 b

[i]Normal distribution. All others were log-transformed before the analysis.

B = boron; Ca = calcium; CEC = cation exchange capacity; Cl^- = extractable chloride; CP = commercial nonfood biomass product; Cu = copper; DM = dried dairy manure; EC = electrical conductivity; Fe = iron; GWW = ground wood waste; K = potassium; Mg = magnesium; Mn = manganese; Na = sodium; P = phosphorus; PP = *Pinus ponderosa* sawdust; S = sulfur; Zn = zinc.

with the highest biochar CECs being approximately one-third that of peatmoss.

The GWW and CP biochars exhibited distinct chemical properties. In fact, CP contained substantially higher contents of NO_3-N, P, and K compared with those in GWW. However, GWW showed lower nutrient concentrations but a higher pH (8.9) than that of CP (7.3). Micronutrient levels were generally low in these two biochars, although GWW contained more Mn (11.0 mg/kg) relative to CP (3.2 mg/kg). The CEC was higher in GWW [46.0 cmol(+)/kg] than in CP [30.0 cmol(+)/kg], while the EC values remained modest in both (3.3–4.6 $mS \cdot cm^{-1}$).

Physical and chemical characteristics of growth media. During the 2015 trial, physical properties (air capacity, water-holding capacity, and total porosity) of the growing media were minimally affected by the different amounts of biochar in the growing media (Table 2). Air capacity ranged from a low of 17% (in 0% PP control) to a high of 24% (20% DM). Water-holding capacity ranged from 48% (in 5% PP) to 56% (in 20% DM). Total porosity ranged from a low of 67% (in 20% PP) to a high of 80% (in 20% DM) (Table 2). A statistical analysis of the main effect of biochar type on air capacity was possible because interactions were absent. The mean air capacity for mixes containing DM was higher (21.1%) than that of the PP mixes (19.3%) (Table 2). Significant interactions were detected for water-holding capacity and total porosity; therefore, a comparison was only possible between the two biochars (DM or PP) within a concentration (0%, 5%, 10%, 15%, or 20%). Water-holding capacities in DM were significantly higher than those in PP at all concentrations except the 0% control, which were similar. Total porosity of the DM was also higher than that of the PP at all concentrations except the control, and total porosity of the DM increased as the amount of DM increased.

During the 2016 trial, interactions were absent for air capacity, water-holding capacity, and total porosity, allowing an analysis of the main effects of biochar or concentration. Air capacity was significantly affected by concentration, but a linear trend in response to concentration was absent. In contrast, water-holding capacity significantly decreased by 1.5% to 9.3% as the concentration of biochar increased compared with the 0% biochar treatment. Neither biochar type nor concentration significantly affected total porosity.

Levels of P, K, Na, and CEC differed significantly by treatment in the 2015 trial, and interactions were detected within all analyses (Table 3); therefore, only the interaction terms were compared for significance between the two biochars within a concentration. The highest amounts of P (5111 mg/kg) and K (13,697 mg/kg) were present in the 20% DM. The concentration of P was significantly higher in DM than in the corresponding PP at all concentrations except the 0% control. Levels of P and K in the media increased as the proportion of DM increased, whereas increasing concentrations of PP resulted in decreasing P levels.

Significantly higher levels of Na were detected in mixes containing DM (Table 3). The Na concentrations ranged from 0.6 meq/100 g in the 0% DM control to a high of 22.2 meq/100 g in the 20% DM. The concentration of Na increased as the concentration of DM increased; however, on the contrary, mixes containing PP had low levels of Na.

The control had the highest CEC at 75.7 cmol(+)/kg (Table 3), and CEC decreased as the concentration of either biochar increased, but it was only significantly different between the DM and PP at 10%, 15%, and 20%. The DM biochar at 10% and 15% contained the higher CEC.

In 2016, levels of P, K, Na and CEC differed significantly by treatment (Table 3). Interactions were present only for K and CEC, allowing a comparison of the main effect of biochar type or concentration for P and Na. The amount of P in the 2016 mixes ranged from a low of 74.3 mg/kg in the 0% CP to a high of 197 mg/kg in the 15% and 20% CP. The P levels increased significantly with increasing concentrations of either of CP or GWW up to 15% biochar, at which point P levels became stable even when with increased biochar concentrations.

Levels of K also significantly varied in response to biochar type and concentration. The highest amount of K (2307 mg/kg) was detected in the 20% CP, whereas the lowest amount was found in both control mixes. Because of significant interactions, biochars were able to be compared within a concentration. The amount of K was significantly higher in CP compared with GWW at all concentrations except the control, which were similar. As the proportion of either CP or GWW increased, so did the amount of K; however, the amount of K in the CP biochar was at least 1.3-times higher than that in any of GWW biochar.

While Na levels differed statistically between treatments, overall, Na levels were low, ranging from 0.7 meq/100 g in either control to a high of 2.7 meq/100 g in the 10% GWW. A significant main effect of Na concentration was detected; as the biochar concentration increased from 0% to 5% and from 5% to 10%, Na levels also increased. However, from 10% to 15% or 15 to 20%,

Table 2. Effects of biochar type and concentration on key physical properties of container media containing 0%, 5%, 10%, 15%, or 20% biochars in 2015 or 2016. The main effects of either biochar type or concentration are presented in the Biochar means or Concentration means column, while interaction means are presented in the shaded portions. Letters denote statistical differences as determined by using least-squares means at the 5% level (n = 3) within either main effects or the interaction means. Values without a letter indicate nonsignificant differences.

2015	Rate (%) 0	5	10	15	20	Biochar means
Air capacity (%)						
DM	18.5	19.2	21.5	22.4	24.4	21.1 a
PP	17.1	21.1	19.6	19.7	19.0	19.3 b
Concentration means	17.8	20.1	20.5	21.0	21.6	
	Biochar × rate (P = 0.0135)					
Water-holding capacity (%)						
DM	51.5	54.6 a	55.2 a	56.1 a	56.2 a	54.7
PP	50.7	48.1 b	48.6 b	50.8 b	48.7 b	49.4
Concentration means	51.1	51.3	51.9	53.4	52.5	
	Biochar × rate (P = 0.00426)					
Total porosity (%)						
DM	70.0	73.8 a	76.6 a	78.5 a	80.6 a	76.1
PP	67.9	69.1 b	68.3 b	70.4 b	67.7 b	68.7
Concentration means	68.9	71.5	72.6	74.7	74.7	
	Biochar × rate (P < 0.0001)					

2016	Rate (%) 0	5	10	15	20	Biochar means
Air capacity (%)						
CP	19.8	23.0	21.3	22.4	25.4	22.3
GWW	23.2	25.1	21.8	23.3	26.4	24
Concentration means	21.4 b	24.1 ab	21.6 b	22.9 ab	25.9 a	
	Biochar × rate (P = 0.0234)					
Water holding capacity (%)						
CP	54.6	51.1	53.2	51.8	49.9	52.1
GWW	53.0	53.3	52.9	50.6	47.7	51.5
Concentration means	53.8 a	52.2 ab	53.1 a	51.2 b	48.8 c	
	Biochar × rate (P < 0.0001)					
Total porosity (%)						
CP	74.3	74.0	74.4	74.2	75.2	74.4
GWW	77.0	78.4	74.6	73.8	74.0	75.6
Concentration means	75.7	76.3	74.5	74.0	74.6	

CP = commercial nonfood biomass product; DM = dried dairy manure; GWW = ground wood waste; PP = *Pinus ponderosa* sawdust.

Na levels remained similar. The 15% CP had the highest CEC 65.0 cmol (+)/kg. The CEC was higher in CP than in GWW for all concentrations except the control, which were equivalent.

Plant growth. In 2015, interactions between biochar type × concentration affected mockorange and spirea heights and shoot dry weights (Table 4). Therefore, comparisons were made between biochar type within each concentration. Spirea shoot dry weight was the highest (20.4 g) in the medium amended with 20% PP, while the lowest (3.7 g) was observed in the 15% DM. Heights decreased by at least 55% in the 15% or 20% DM, but height was similar for spirea in the control, in any of the PP-supplemented mixes, and in 5% DM. The highest shoot dry weight in mockorange (13.9 g) was observed in the 0% PP control. The lowest plant height and shoot dry weight in mockorange were observed in 15% DM. The mockorange plants growing in 5%, 10%, 15%, and 20% PP produced significantly higher shoot dry weights compared with plants in the corresponding DM. Conversely, plant heights in the 10% DM and 15% DM were significantly lower than those in the corresponding PP.

In 2016, interactions between biochar type × concentration affected spirea height and shoot dry weight as well as firechalice shoot dry weight (Table 4). Therefore, comparisons were made between biochar types within a concentration, except for firechalice canopy diameter, wherein the main effects of biochar type or concentration were evaluated. The highest shoot dry weight of spirea plants (32.4 g) was produced at 10% CP, whereas the lowest (23.8 g) was observed for spirea plants growing in 20% GWW. Media containing 10% CP generated the highest shoot dry weight for firechalice (15.5 g), whereas the lowest (11.6 g) was observed for firechalice plants grown in 0% CP. A trend was lacking among spirea plant heights when compared between the two biochars at each concentration. Significant larger shoot dry weights were produced in the 10%, 15%, and 20% CP compared with the equivalent GWW. Growth medium containing 10% CP increased spirea shoot dry weight by 12% when compared with control plants.

Significant differences between treatments involving biochar type or concentration were absent for firechalice canopy diameter, and no obvious statistical trend was observed for shoot dry weight comparisons between biochar types within a concentration. However, mixes containing 5%, 10%, or 15% CP increased firechalice shoot dry weight by at least 21% compared with control plants, whereas the 20% CP produced a shoot dry weight similar to that of the control plants. Incorporation of GWW reduced both spirea and firechalice shoot dry weight at least 7.3%.

Discussion

Of the raw biochars, DM provided the most nutrients; however, at the same time, it

Table 3. Effects of biochar type and concentration on chemical properties including available P, K, and Na and CECs of container media containing 0%, 5%, 10%, 15%, or 20% biochar. The main effects of either biochar type or concentration are presented under the Biochar means or Concentration means column, while interaction means are presented in the shaded portions. Letters denote statistical differences as determined by using least-squares means at the 5% level ($n = 4$) within either main effects or the interaction means. Values without a letter indicate nonsignificant differences. A lognormal distribution was used for P, K, and Na in 2015 and for K and Na in 2016.

	2015							2016					
	Rate (%)							Rate (%)					
	0	5	10	15	20	Biochar means		0	5	10	15	20	Biochar means
P (mg/kg)							P (mg/kg)						
DM	1097	2263 a	3621 a	4059 a	5111 a	2876	CP	74.3	136	166	197	197	154
PP	1294	885 b	799 b	775 b	653 b	858	GWW	93.6	133	152	155	155	138
Rate means	1192	1416	1701	1774	1827		Rate means	85.3 c	134.5 b	159 ab	176 a	175 a	
	Biochar × rate ($P < 0.0001$)												
K (mg/kg)							K (mg/kg)						
DM	4020	6762 a	11,303 a	12,623 a	13,697 a	8811	CP	905	1360 a	1863 a	2034 a	2307 a	1608
PP	4267	3526 b	3315 b	2990 b	3329 b	3461	GWW	847	1020 b	1222 b	1273 b	1310 b	1120
Rate means	4141	4882	6121	6144	6753		Rate means	875	1178	1509	1609	1739	
	Biochar × rate ($P < 0.0001$)							Biochar × rate ($P = 0.0002$)					
Na (meq/100 g)							Na (meq/100 g)						
DM	0.6	6.2 a	12.5 a	16.5 a	22.2 a	7.0	CP	0.7	1.6	2.2	2.2	2.5	1.6
PP	0.6	0.5 b	0.6 b	0.5 b	0.6 b	0.6	GWW	0.7	1.0	2.7	2.6	2.6	1.7
Rate means	0.6	1.8	2.7	3.0	3.7		Rate means	0.7 c	1.2 b	2.4 a	2.4 a	2.5 a	
	Biochar × rate ($P < 0.0001$)												
CEC (cmol (+)/kg)							CEC (cmol (+)/kg)						
DM	75.7 a	62.3	62.7 a	57.0 a	35.3 b	58.6	CP	62.3	63.3 a	64.7 a	65.0 a	53.0 a	61.7
PP	65 b	64.3	53 b	42.0 b	41.7 a	53.2	GWW	62.3	47.0 b	45.3 b	44.0 b	45.0 b	48.7
Rate means	70.3	63.3	57.8	49.5	38.5		Rate means	62.3	55.2	55.0	54.5	49.0	
	Biochar × rate ($P < 0.0001$)							Biochar × rate ($P = 0.0006$)					

CEC = cation exchange capacity; CP = commercial nonfood biomass product; DM = dried dairy manure; GWW = ground wood waste; K = potassium; Na = sodium; P = phosphorus; PP = *Pinus ponderosa* sawdust.

also contained high concentrations of salts, which negatively impacted plant growth. In addition, the high pH of DM most likely inhibited plant growth. Leaching could reduce some of the toxicity in this biochar; however, it would also result in the loss of desirable nutrients. However, CP provided additional beneficial nutrients compared with standard mix components of bark or peat, but at levels significantly lower than those in the DM biochar (Table 1). Regarding overall nutrient composition, the CP appeared best suited for potentially growing plants because it offered additional N, P, and K while containing only minor levels of Na and Cl.

Increased CEC is frequently cited as a key benefit of incorporating biochar (Buss et al. 2016; Housley et al. 2015); however, all four biochars tested had poor CECs. Incorporation of only peatmoss resulted in the growing media having the highest CECs (Table 3). The differences observed between the various biochars were likely caused by the different types of starting biomass used or the temperature during pyrolysis (Bedussi et al. 2015; Buss et al. 2016; Cantrell et al. 2012; Prasad et al. 2017; Zhao et al. 2013). Zhao et al. (2013) determined that the characteristics in a final biochar that were most influenced by the starting material were total organic carbon, fixed carbon, and mineral elements; however, biochar surface area and pH were mostly impacted by the temperature of pyrolysis. Because three of the four biochars used (DW, PP, and GWW) were made at either the University of Idaho or Washington State University, some of the poor biochar characteristics, especially the low CECs observed, could have been caused by pyrolysis conditions.

The suitability of each biochar as a growth substrate amendment was also evaluated with the inclusion of peatmoss and bark in the experimental media. All experimental media had physical properties (air capacity, water-holding capacity, and total porosity) that were acceptable for container plant production regardless of the percentage of biochar in the mix. Water-holding capacities were affected by the biochar content in GWW, CP, and DM. As the concentration of GWW or CP increased, media water-holding capacity decreased; however, in the case of DM, when the concentration increased, the water-holding capacity also increased. Other studies have also noted that biochar substitution for peatmoss in growing media alters the physical characteristics of the media. Fascella et al. (2018) noted a decrease in water content as the concentration of conifer wood biochar in a peatmoss/biochar mix increased, whereas Kim et al. (2017) observed that incorporation of rice hull biochar into a coir dust, perlite, and vermiculite mix increased the water content of the growth media. Kaudal et al. (2016) observed an increase in air-filled porosity and bulk density in a composted pine bark mix with the incorporation of urban biochar made from biosolids and green waste.

An evaluation of key chemical properties (P, K, Na, pH, and CEC) in response to biochar type and concentration in the mixes

Table 4. Increase in plant height or plant canopy diameter and shoot dry weight of spirea, mockorange, and firechalice grown in the media amended with varying amounts of PP, DM, CP, or GWW biochar. Letters within a column within a year indicate significant differences as determined by using least-squares means at the 5% level (n = 4). Values without a letter indicate nonsignificant differences.

2015							2016						
	Rate (%)							Rate (%)					
	0	5	10	15	20	Biochar means		0	5	10	15	20	Biochar means
Mockorange height (cm)							Spirea height (cm)						
DM	13.7	13.7 a	7.2 b	4.5 b	9.4	9.7	CP	33.7 a	31.1	34.2 a	28.9	31.4	31.9
PP	13.6	9.6 b	11.2 a	8.6 a	9.1	10.4	GWW	28.6 b	30.6	27.9 b	33.3	30.3	30.2
Rate means	13.6	11.6	9.2	6.5	9.2		Rate means	31.1	30.9	31.1	31.1	30.8	
		Biochar × rate (P = 0.0135)							Biochar × rate (P = 0.0234)				
Mockorange shoot dry weight (g)							Spirea shoot dry weight (g)						
DM	12.7	10.0 b	8.1 b	4.7 b	8.8 b	8.9	CP	28.7	27.0	32.4 a	30.2 a	29.4 a	29.5
PP	13.9	13.1 a	12.3 a	11.8 a	14.1 a	13.1	GWW	30.1	26.7	26.0 b	24.0 b	23.8 b	26.1
Rate means	13.3	11.6	10.2	8.3	11.5		Rate means	29.4	26.9	29.2	27.1	26.6	
		Biochar × rate (P = 0.0259)							Biochar × rate (P < 0.0001)				
Spirea height (cm)							Firechalice canopy diameter (cm)						
DM	25.9	27.7	18.5 b	6.4 b	11.7 b	18.0	CP	32.9	33.0	33.0	30.5	29.6	31.8
PP	27.7	28.8	27.5 a	26.4 a	25.9 a	27.2	GWW	32.7	29.8	31.3	30.7	31.4	31.2
Rate means	26.8	28.2	23.0	16.4	18.8		Rate means	32.8	31.4	32.2	30.6	30.5	
		Biochar × rate (P < 0.0001)											
Spirea shoot dry weight (g)							Firechalice shoot dry weight (g)						
DM	19.4	18.5	13.4 b	3.7 b	6.5 b	12.3	CP	11.6 b	14.1	15.5	15.3 a	12.9	13.9
PP	19.6	19.1	20.1 a	18.0 a	20.4 a	19.4	GWW	15.4 a	12.7	14.2	13.1 b	13.9	13.9
Rate means	19.5	18.9	16.8	10.9	13.4		Rate means	13.5	13.4	14.9	14.2	13.4	
		Biochar × rate (P < 0.0001)							Biochar × rate (P = 0.0007)				

CP = commercial nonfood biomass product; DM = dried dairy manure; GWW = ground wood waste; PP = *Pinus ponderosa* sawdust

mirrored the chemical analysis of the pure biochars. Incorporation of DM increased the levels of P, K, Na, and pH. A key chemical characteristic, EC, was confounded and subsequently excluded from our analysis because samples submitted for chemical analysis in the 2015 study were sampled after the Osmocote had been added. However, preliminary EC readings were completed at planting before fertilizer incorporation using the saturated extraction method and a handheld EC meter. These preliminary EC readings in DM were 1.108 mS·cm^{-1} in control, 3.17 mS·cm^{-1} in 5%, 5.17 mS·cm^{-1} in 10%, 6.13 mS·cm^{-1} in 15%, and 10.08 mS·cm^{-1} in 20%. In general, an EC reading greater than 2 mS·cm^{-1} denotes that the medium is not recommended unless salt-tolerant species are being grown (Marx et al. 1999). Our levels (3–10 mS·cm^{-1}) indicated that salt levels were critically high, especially in the 15% and 20% DM treatments; therefore, those pots were leached before planting. Without leaching, few, if any, plants would have survived in the15% or 20% DM. Even though DM contained the highest levels of P and K, which should have been most beneficial for plant growth, the amount of salt in most of the DM was higher than optimal levels. This toxicity was observed in the difference in mortality between the PP and DM biochars. Mockorange plant mortality within mixes amended with PP biochar ranged from 0% to 15%, whereas mortality in the DM biochar ranged from 20% to 55%. Spirea were less affected than mockorange, except for the 15% and 20% DM, where 50% and 5% of the spirea plants died, respectively. Notably, plants grown in the PP survived and showed sustained growth. The highest mortality (>50%) for both species occurred in the 15% DM treatment. Mortality was low in 2016, with all spirea surviving and only one firechalice dying in the 5% GWW, again supporting the idea that DM contained salt levels that were too high. The EC of the other biochar mixes was much lower, ranging from 0.361 mS·cm^{-1} to a high of 0.932 mS·cm^{-1} (data not shown).

An increase in EC with increasing biochar concentrations has been noted by others; however, the ECs of the final mixes were much lower than those of DM. Vaughn et al. (2013) saw an increase in EC when 5%, 10%, or 15% pelletized straw or wood biochars were incorporated compared with a 50% peat mix. However, ECs for the study ranged from 1.63 mS·cm^{-1} in the 50% peat control to a high of 1.9 mS·cm^{-1} in the 15% straw biochar mix. Cantrell et al. (2012) evaluated the effect of the temperature of pyrolysis on biochars made from dairy manure, feedlot manure, poultry litter, separated swine solids, and turkey litter. The ECs were measured in a 1% (w/v) suspension in deionized water prepared by shaking at 100 rpm for 2 h. The resulting EC of the different biochars ranged from 0.194 mS·cm^{-1} (swine solids, high-temperature pyrolysis) to 2.217 mS·cm^{-1} (poultry litter, high-temperature pyrolysis). The dairy manure EC ranged from 0.561 to 0.702 mS·cm^{-1} depending on the pyrolysis temperature, whereas the feedlot manure biochars had ECs ranging from 0.713 to 1.140 mS·cm^{-1} depending on the pyrolysis temperature. In contrast, Prasad et al. (2018) evaluated four commercial grade biochars and found they contained negligible amounts of N, P, and generally had high levels of K. Incorporation of the biochars at 10%, 25%, or 50% with peat caused a reduction in EC and an increase in media pH and K levels. Furthermore, Fornes et al. (2017) evaluated the characteristics of coir mixed with 0%, 10%, 25%, 50%, 75%, or 100% biochar made from forest waste or olive mill waste. The EC of the olive mill waste was also very high, ranging from 1.39 mS·cm^{-1} (10% biochar) to 11.46 mS·cm^{-1} (100% biochar), although the EC decreased over the course of the study, and the authors noted that EC was not a pernicious factor at high doses for the two tomato cultivars grown.

The dairy manure used to make the experimental biochar was collected from a settling lagoon and then dried before pyrolysis. This manure may have absorbed additional salts while it was in the lagoon; therefore, a biochar made from raw dairy manure or feedlot manure may be acceptable. The DM also had the highest pH of any growing media in the experiment (7.2 and 7.82 in 15% and 20%, respectively) and low CECs (Table 2). The high pH in mixes containing greater than 15% DM could have caused micronutrient deficiencies; consequently, increasing concentrations of DM caused a reduction in media CEC, both of which could contribute to poor plant growth. Among the other experimental media, those containing CP or GWW did provide some benefits when compared with a typical bark and peatmoss mix. Both provided low levels of K and P (CP slightly more); however, they added very little Na while maintaining a pH of approximately 6.3. While the incorporation of the CP increased CECs only slightly, the other values remained similar to those of the control. In contrast, the incorporation of GWW resulted in lower CECs compared with the control. The PP contributed insignificant amounts of nutrients; moreover, its incorporation resulted in a lower pH ($\sim$5.5 average) and a reduction in CEC (Table 2).

Plant growth in response to the different biochars varied considerably. Three of the biochars (DM, PP, or GWW) were found to be detrimental to either plant height or shoot dry weight in at least one of the plant species evaluated. However, mixes containing GWW or PP were less detrimental. Specifically, GWW caused a reduction in shoot dry weight for both spirea and firechalice, although plant heights remained unaffected. The PP resulted in a reduction in mockorange plant height, while shoot dry weight remained unchanged. Notably, spirea plants grown in media with up to 20% PP were similar in size (height and dry weight) compared with the control plants. In contrast, DM had a negative effect on both species, leading to a reduction in both shoot dry weight and height when used at concentrations higher than 5%. Mortality rates also increased significantly with the use of DM, reaching up to 50% in the 15%. Fewer plants died in the 20% DM, likely because of the leaching treatment applied at planting. The 15% pots were leached twice, whereas the 20% were leached three times. The improved growth (increased dry weights and plant heights) observed with leaching strongly indicated that mortality was caused by salt toxicity, which was mitigated through leaching.

Only one of the biochars, CP, improved plant growth. Incorporation of 10% CP resulted in increased shoot dry weight for spirea, while 5%, 10%, or 15% CP improved shoot dry weight for firechalice. These mixed results align with findings in the literature because the effects of biochar on plant growth have varied, with studies showing negative, neutral, or positive impacts depending on the biochar type, concentration, and plant species. For instance, Fornes et al. (2017) found that biochar derived from forest waste or olive mill waste, as well as a hydrochar, all negatively affected tomato plant growth and yield, although they did not impact fruit quality. Similarly, Prasad et al. (2018) evaluated the effects of four commercial biochars on tomato shoots dry weight and fresh weight. They found that incorporation of 10% in one of the biochar increased shoot dry weights, while all other treatments produced plants with equivalent or smaller dry weight. Additionally, seedling fresh weight was inhibited by increasing biochar concentration across all biochars. Guo et al. (2018) evaluated poinsettia growth in response to biochar incorporation and found that plants grown in up to 40% biochar were comparable to those grown in the control; however, when the biochar ratio was increased to 80%, dry weight decreased. Housley et al. (2015) studied the effects of four rates of *Eucalyptus saligna* biochar on the growth of lilly pilly (*Acmena smithii*), pansy, and viola and found that the biochar failed to significantly affect the growth of these three species. Vaughn et al. (2013) assessed the impact of hardwood or straw biochars on the growth of tomato and marigold and observed that the addition of either biochar did not affect the dry weight in tomatoes but increased plant height in all treatments. Kim et al. (2017) found that the incorporation of 5% rice hull biochar increased the dry weight of kale by 150% compared with the control media.

Conclusion

Replacing peatmoss with biochar as a container substrate offers a sustainable solution to the environmental issues associated with peatland mining and drainage while also delivering several agronomic and economic benefits. These include enhanced protection of peatland ecosystems, improved water and fertilizer use efficiency, reduced greenhouse gas emissions, and potential cost savings (Yu et al. 2023).

Our study found that incorporating 10% CP improved shoot dry weight in spirea and firechalice plants, indicating its potential as a viable growth medium substrate. However, the other tested biochars (DM, PP, and GWW) negatively affected at least one plant species, highlighting the variability in biochar suitability. Contrary to previously reported benefits, increased CEC, pH adjustment, and enhanced water retention were absent across the biochar-amended media.

These findings emphasize the critical need for thorough evaluations of biochar properties before their widespread use in nursery production. Postpyrolysis treatments, such as leaching, may help mitigate issues with high salt contents, potentially expanding the applicability of biochar in horticultural substrates. Given their highly variable characteristics, biochars must be carefully selected and possibly treated to ensure consistent and beneficial outcomes for plant growth.

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