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Biochar as a replacement for perlite in greenhouse soilless substrates

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Biochar as a replacement for perlite in greenhouse soilless substrates

by

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A thesis submitted to the graduate faculty

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ABSTRACT

Biochar is a solid, carbonaceous coproduct of the pyrolysis process used for biofuel production. Many field studies have shown improved chemical and physical properties of soil after amendment with biochar. The benefits of biochar may extend to soilless substrates used in the greenhouse industry, and the porous nature of biochar may make it a suitable replacement for perlite in greenhouse substrates. The objectives of this research were to determine the most suitable biochar particle size and percentage for use in a greenhouse substrate, to determine if biochar can eliminate the need for amendment with limestone, and to demonstrate plant growth in substrates with biochar as a component.

We obtained four sizes of prescreened hardwood biochar and blended each with sphagnum peat to create 40 substrates for experimental trials. The pH of leachate from each substrate was recorded over a 16-week period. Substrate pH increased as the percentage of biochar increased. At the same percentage of biochar in the substrate, decreasing the particle size of biochar increased substrate pH. Several biochar-sphagnum peat mixtures, without limestone amendment, led to a substrate pH appropriate for container-grown plants. Eight of the nine substrates selected for evaluation met recommended physical parameters for use in containers for greenhouse crop production. One substrate, 30% BC_{10} blended with 70% sphagnum peat, was similar to the control, Sunshine LC1 (Sun Gro Horticulture, Agawam, MA) in all measures except bulk density. Plants grown in biochar-containing substrates were compared to plants grown in a commercial substrate that contained sphagnum peat, perlite, and limestone (Sunshine LC1). Plants grew in each substrate for 27 or 35 days. Electrical conductivity and pH were measured 14 days after transplanting and at the end of each trial.

Results varied among trials and crops grown. Many biochar-based substrates produced plants with shoot dry mass greater than or equal to the control. These results demonstrate the potential for biochar to replace perlite and eliminate the limestone amendment needed for commercial greenhouse soilless substrates based on sphagnum peat. Soilless substrates containing biochar as a replacement for perlite and limestone can successfully be used for greenhouse plant production.

CHAPTER 1. GENERAL INTRODUCTION

Current concerns with sustainability and the environment have resulted in many new products that address such concerns, as well as new or adapted practices that reduce the use of natural resources and have a positive impact on the environment. In the horticulture industry, there is growing awareness of these issues, and an opportunity to capture sales with environmentally friendly, sustainable products. The soilless substrates used by most greenhouse operations today may not be sustainable, but they have the potential to become a more earth-friendly, sustainable product by replacing key components.

Until the mid-1970s, greenhouse crop producers used a soil-based mix as a substrate for the production of nearly all greenhouse crops. This mix generally was about one-third field soil, one-third sphagnum peat moss, and one-third horticultural-grade perlite. In the mid-1970s, greenhouse growers began to look for an alternate substrate system because the soil-based substrate was too heavy for shipping to distant markets and it was becoming difficult to find good sources of clean field soil. In the mid 1950s, researchers at Cornell University developed the Cornell A and Cornell B soilless mixes. Cornell A consisted of 50% sphagnum peat moss and 50% horticultural, medium-grade vermiculite. The Cornell B mix consisted of 50% sphagnum peat moss and 50% horticultural grade perlite (Nelson, 2012). Since then, soilless mixes have evolved over time, and today they are generally mixtures of about 2/3 sphagnum peat moss and 1/3 perlite and/or vermiculite. The ratio of the components in soilless substrates varies among manufacturers and intended uses, but most commercial mixes contain the components and approximate percentages given above. These mixes are amended with dolomitic or calcitic limestone to adjust the pH of the substrate to a level that optimizes the availability of nutrients to the plants (Nelson, 2012).

Biochar is a term for charcoal intended for use as a soil amendment (Lehmann and Joseph, 2009). It is a carbonaceous residue generated by heating biomass in the absence of oxygen, a process known as pyrolysis, which transforms organic matter into a vapor phase and the solid biochar residue. Volatiles generated during pyrolysis remain as syngas or are condensed into bio-oils, which can be used directly or refined to produce renewable liquid fuels. If the production of renewable fuels via biomass pyrolysis proves economical, the amount of biochar available for other applications will increase (Laird et al., 2009).

Use of biochar as a soil amendment is attracting research interest because biochar enhances soil quality. Biochar additions to soil also are considered a means of sequestering carbon, thereby helping to mitigate global climate change (Laird, 2008). Much biochar research has focused on the effects of biochar in tropical soils, with results indicating improved plant growth (Steiner et al., 2007), increased N retention (Steiner et al., 2008), and increased bioavailability and plant uptake of supplemented nutrients (Atkinson et al., 2010). Biochar amendments to soils typically in the Midwestern United States increased water retention, increased cation exchange capacity, and raised pH (Laird et al., 2010a). Additionally, leaching of N, P, and Mg was decreased in biochar-amended soils (Laird et al., 2010b).

Widespread application of biochar to agronomic soils faces several potential challenges including transport, handling, and protocols for incorporation of biochar into the field, as well as a lack of short-term return on investment (Laird, 2008). Horticultural field applications of biochar are likely to face the same challenges; however, the smaller spatial footprint and greater relative value of horticultural crops may provide more economic incentive than the use of biochar in agronomic crop production.

Potential for horticultural use of biochar exists in the soilless substrates used for container production of greenhouse crops. Because biochar production diverts a raw material that potentially could be turned into fuel, energy companies have little incentive to produce biochar (Laird, 2008). Using biochar in substrates potentially adds value to biochar, while creating an opportunity for carbon sequestration (Dumroese et al., 2011).

Biochar previously has been evaluated in soilless substrates. Santiago and Santiago (1989) discussed a system for growing plants outdoors in Malaysia using processed charcoal chips and chunks as a container substrate. This specialized system was tailored to the rainy climate, and plants grew well as long as nutrition was provided via resin-coated, slow-release fertilizers. Dumroese et al. (2011) studied the use of pelleted biochar in nursery container substrates. The optimal substrate, which contained 75% peat moss and 25% biochar pellets, was found suitable for production of containerized nursery plants. Tian et al. (2012) found improved growth of *Calathea rotundifola* cv. Fasciata Korn in biochar made from urban green waste mixed with peat in equal parts, compared to growth in peat or green waste biochar alone.

Biochar also has been studied as an amendment to soilless substrates, and it provided improved plant growth as well as biochar-induced systemic resistance to disease (Elad et al., 2010; Graber et al., 2010). Altland and Locke (2012) demonstrated that additions of biochar up to 10% by volume decreased peak nitrate and phosphate leaching by slowing their release over time. This suggests nitrate could be applied less frequently due to the capacity of biochar to hold nitrate and release it to the plant roots slowly. Additionally, phosphate and K applications could be reduced because these nutrients are present in biochar and are released over time (Altland and

Locke, 2012). Field studies also have indicated the fertilizer potential of biochar (Glaser et al., 2002).

Hardwood biochar is relatively lightweight and porous, and it might substitute for perlite often used in soilless greenhouse substrates. Perlite is crushed volcanic rock heated to create an expanded, porous, lightweight material used for aeration (Nelson, 2012). If a cost effective material could be identified to replace perlite, it would become attractive to companies manufacturing soilless mixes for the greenhouse industry and to growers using these substrates to produce greenhouse crops. Other materials that have been studied as substitutes for perlite in greenhouse substrates include shredded rubber (Evans and Harkess, 1997), bovine bone (Evans, 2004), parboiled fresh rice hulls (Evans and Gachukia, 2004), and a glass-based aggregate known as Growstones (Evans, 2011). Shredded rubber and bovine bone released undesirable chemicals (Evans and Harkess, 1997; Evans, 2004), and Growstones and parboiled fresh rice hulls were acceptable for use in soilless substrates (Evans, 2011; Evans and Gachukia, 2004).

The overall objective of this project was to evaluate the capacity of biochar to replace perlite in commercial greenhouse soilless substrates. The specific objectives were to: 1) determine the optimum biochar particle size for use in a substrate; 2) determine the optimum ratio of biochar to sphagnum peat; 3) determine if the use of biochar can eliminate the need for amendment with limestone; and 4) demonstrate plant growth in substrates with biochar as a component.

Thesis organization

This thesis follows the journal paper format. Chapter 1 includes a general introduction to the thesis with background and literature review. Chapters 2 and 3 are the papers to be submitted to *HortScience*, and correspond to the objectives outlined above. Specifically, Chapter 2 details the research done on particle size and ratio as well as the experiments to determine potential for elimination of limestone amendment. This chapter also contains a more extensive literature review of previous research on alternative components in soilless substrates and the determination of the physical properties of such substrates. Chapter 3 is focused on demonstration of plant growth in biochar-containing substrates. Chapter 4 provides a summary and conclusions drawn from the work, as well as recommendations for future research. References for the contents of each chapter are given at the end of the individual chapters. Tables and figures are placed at the end of the chapter in which they are first referenced.

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CHAPTER 2. pH AND PHYSICAL PROPERTIES SHOW BIOCHAR CAN REPLACE PERLITE IN GREENHOUSE SUBSTRATES

A paper to be submitted to *HortScience*

Jake I. Northup[1,3], Richard J. Gladon[1,4], and David A. Laird[2,4]

Abstract

Biochar is a carbonaceous material that is a coproduct of pyrolysis of biomass. Many field studies have shown improved chemical and physical properties of soil after amendment with biochar. The benefits of biochar may extend to soilless substrates used in the greenhouse industry, and the porous nature of biochar may make it a suitable replacement for perlite in greenhouse substrates. The objectives of our research were to determine the most suitable biochar particle size and percentage for use in a greenhouse substrate. We obtained four sizes of prescreened hardwood biochar and blended each with sphagnum peat in increments of 10% to create 40 substrates. The pH of leachate from each substrate was recorded over a 16-week period. Substrate pH increased as the amount of biochar increased and as the particle size of biochar decreased. Several biochar percentages, without limestone amendment, led to a substrate pH appropriate for container-grown plants. Eight of the nine substrates we selected for evaluation met recommended physical parameters for use in containers for greenhouse crop production. One substrate, 30% BC_{10} blended with 70% sphagnum peat, had physical

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properties similar to the control, Sunshine LC1 (Sun Gro Horticulture, Agawam, MA) in all measures except bulk density. Our results demonstrate biochar can replace perlite and eliminate the limestone amendment needed for commercial greenhouse soilless substrates.

Introduction

Biochar is a term for charcoal intended for use as a soil amendment (Lehmann and Joseph, 2009). It is a carbonaceous residue generated by heating biomass in the absence of oxygen, a process known as pyrolysis, which transforms organic matter into a vapor phase and the solid biochar residue. Volatiles generated during pyrolysis remain as syngas or are condensed into bio-oils, which can be used directly or refined to produce renewable liquid fuels. If the production of renewable fuels via biomass pyrolysis proves economical, the amount of biochar coproduct available for other applications will increase (Laird et al., 2009).

Use of biochar as a soil amendment is attracting research interest because biochar enhances soil quality. Biochar additions to soil also are considered a means of sequestering carbon, thereby helping to mitigate global climate change (Laird, 2008). Much biochar research has focused on the effects of biochar in tropical soils, with results indicating improved plant growth (Steiner et al., 2007), increased N retention (Steiner et al., 2008), and increased bioavailability and plant uptake of supplemented nutrients (Atkinson et al., 2010). Biochar amendments to typical Midwestern United States agricultural soil increased water retention, increased cation exchange capacity, and raised pH (Laird et al., 2010a). Additionally, leaching of N, P, and Mg was decreased in biochar-amended soils (Laird et al., 2010b).

Widespread application of biochar to agronomic soils faces several potential challenges including transport, handling, and protocols for incorporation of biochar into the field, as well as a lack of short-term return on investment (Laird, 2008). Horticultural field applications of biochar are likely to face the same challenges; however, the greater relative value and the smaller spatial footprint of horticultural crops may provide more economic incentive for the use of biochar than agronomic crops. Potential for additional horticultural use of biochar exists in soilless substrates used for container production of greenhouse crops.

Biochar has been studied as an amendment in soilless substrates, and it has provided improved plant growth as well as biochar-induced systemic resistance to disease (Elad et al., 2010; Graber et al., 2010). Altland and Locke (2012) evaluated the effect of biochar on nutrient retention and release, and they have shown addition of biochar up to 10% by volume decreased nitrate and phosphate leaching by slowing their release over time. Santiago and Santiago (1989) evaluated a system for growing containerized plants outdoors in Malaysia by using processed charcoal chips and chunks as a root substrate. Plants grew well in this specialized system, tailored to the rainy climate, as long as nutrition was provided via slow-release, resin-coated fertilizers. Dumroese et al. (2011) studied the use of pelleted biochar in nursery containers, and they found a substrate containing 75% peat moss and 25% biochar pellets was suitable for use during nursery-crop production. Tian et al. (2012) found biochar made from urban green waste mixed with peat (species not identified) in equal parts improved growth of *Calathea rotundifola* cv. Fasciata Korn compared to growth in peat alone or green-waste biochar alone. More research is needed to determine what role biochar can play in soilless substrates, especially those used in commercial production of greenhouse crops.

Hardwood biochar is relatively lightweight and porous, and it might substitute for perlite often used in soilless greenhouse substrates. Perlite is crushed volcanic rock heated to create an expanded, porous, lightweight material used for aeration (Nelson, 2012). Other materials that have been studied as substitutes for perlite in greenhouse substrates include shredded rubber

(Evans and Harkess, 1997), bovine bone (Evans, 2004), parboiled fresh rice hulls (Evans and Gachukia, 2004), and a glass-based aggregate known as Growstones (Evans, 2011). Shredded rubber and bovine bone released undesirable chemicals (Evans and Harkess, 1997; Evans, 2004), whereas Growstones and parboiled fresh rice hulls were acceptable for use in soilless substrates (Evans, 2011; Evans and Gachukia, 2004).

Our overall objective was to evaluate the capacity of biochar to replace perlite in commercial greenhouse soilless substrates. Our specific objectives were to determine: 1) the optimum biochar particle size for use in a substrate; 2) the optimum ratio of biochar to sphagnum peat; and 3) if the use of biochar can eliminate the need for amendment of the substrate with limestone.

Materials and Methods

Substrate preparation

Four sizes of pre-screened hardwood biochar were obtained from a commercial charcoal-production company (Royal Oak Charcoal, Roswell, GA). The four sizes of biochar were BC_4 (largest), BC_6, BC_{10}, and BC_{20} (smallest). Particles of BC_4, BC_6, BC_{10}, and BC_{20} passed through sieves with openings of 6.35 mm, 3.36 mm, 2.38 mm, and 0.841 mm, respectively, and were retained on sieves with openings of 2.38 mm, 1.19 mm, 0.595 mm, and 0.420 mm, respectively. Each biochar particle size was blended with sphagnum peat (Conrad Fafard, Inc., Agawam, MA), by volume, in 10% increments from 10% biochar to 100% biochar, resulting in 40 biochar-containing substrates. Components were measured, layered in a rotary concrete mixer, and blended for 1 min at 45 revolutions per minute. After mixing, the substrates were stored dry in plastic bags until use. A substrate of 100% sphagnum peat and a standard commercial soilless substrate composed of sphagnum peat and perlite and amended with dolomitic limestone and a starter charge of fertilizer (Sunshine LC1, Sun Gro Horticulture, Agawam, MA) were used as controls.

pH and electrical conductivity

Each substrate was used to fill five 10.2-cm pots with a volume of 601 cm^3 and five 15.2-cm azalea pots with a volume of 1637 cm^3, without plants. Pots were watered and held on greenhouse benches 16 weeks under natural day length at 25 ± 5 °C. Pots were irrigated with tap water (8.1 pH, 0.47 $mS\bullet cm^{-1}$ electrical conductivity, 45.73 $mg\bullet L^{-1}$ calcium carbonate equivalent) to maintain appropriate moisture in the substrate. pH and electrical conductivity were determined by using the PourThru extraction method described by Cavins et al. (2000), and a HANNA combination meter (HI 9811, HANNA Instruments, Inc., Woonsocket, RI). The pH and electrical conductivity of each substrate was measured 14 times during the experiment, at approximately one-week intervals.

Physical testing

Nine substrates, 20%, 30%, and 40% biochar in factorial combination with BC_6, BC_{10}, and BC_{20}, were selected for physical testing. These substrates were selected on the basis of observed pH ranges that were near the pH range of the commercial control substrate. Consideration also was given to particle size and aggregate ratios that resembled those typically found in soilless substrates. Physical properties were determined with aluminum porometers (7.6 cm height by 7.6 cm diameter) with a volume of 347.5 cm^3, by using methods described by Fonteno and Bilderback (1993). Container capacity was calculated as wet weight (after 60 min drainage) minus dry weight, divided by sample volume. Air space was calculated as total volume of drained water divided by sample volume. Total porosity was calculated as the sum of container capacity and air space (Fonteno and Bilderback, 1993). Container height influences container capacity and air space (Nelson, 2012), and therefore, these measures were specific to the 7.6 cm-tall containers used in this study. Bulk density ($g•cm^{-3}$) was determined for each substrate tested. Physical properties of the three sizes of biochar and horticultural perlite (Therm-O-Rock East, Inc., New Eagle, PA) also were determined.

Data analysis

Data for each experiment were analyzed using Statistical Analysis System (SAS) software version 9.3 (SAS Institute Inc., 2010). Because pH observations could not be made on all experimental units on the same day, regression analysis was conducted to develop models that describe the change in pH for each treatment over time and that allow for comparisons to be made between predicted treatment values at specific times. Observed pH values increased over time to a point where a plateau was reached and values no longer increased. This pH plateau (8.2) was based upon accumulation of calcium carbonate, or its equivalent carbonates and bicarbonates, from the tap water and the biochar. A segmented regression model was fitted to each treatment to describe this trend. Analysis of variance was conducted to test for differences between predicted substrate pH values at 14, 28, 42, 56, 70, 84, 98, and 112 days after trial initiation. A least significant difference mean separation test was conducted to determine specific differences between predicted treatment values at these times. Additionally, the slice option in SAS was used to determine if the interaction between particle size and ratio was significant at specific times. Analysis of variance also was performed to assess the influence of biochar on substrate physical properties. Treatment means were compared with Fisher's least significant difference test at $P \leq 0.05$. Physical properties of the prepared substrates and the aggregate components were evaluated separately.

Results

Substrate pH and electrical conductivity

For each size of biochar, increasing the amount of biochar increased substrate pH (Fig. 2.1). As the percentage of biochar increased, the pH difference between successive ratios came to a point where high ratios of biochar had a pH similar to the 100% biochar treatment. The point where these values converged was different for each biochar size and was between 50% and 70%. BC_{20} reached this point with the lowest biochar amount, whereas BC_4 reached this point with the highest amount. Substrates at this point held a pH value similar to biochar alone throughout the remainder of the experiment. In some cases, the pH of 80% or 90% biochar was greater than the 100% treatment (data not presented). During the first 10 to 12 weeks of the experiment, values for 100% biochar increased to a plateau at about pH 8.2, where values remained for the remainder of the experiment. A similar plateau trend was observed for all substrates and occurred earliest with greater percentages of biochar (Fig. 2.1).

Substrate pH increased as the particle size of biochar decreased (Fig. 2.2). Differences between pH values of each particle size were greatest in the lowest ratios and decreased as the percentage of biochar increased. As percentages of biochar increased, differences between sizes decreased to the point where pH was similar regardless of biochar size. At day 14, pH associated with particle size was different for all biochar ratios ($P \leq 0.05$) except 100%. Biochar at 80% and 90% were the same for BC_6, BC_{10}, and BC_{20}, but the pH of the BC_4 ratios was less and different from the rest. This trend continued until day 35 when particle size was not different for the 80% and 90% percentages, as well as 100%, and they stayed the same until the end of the experiment. At day 84, particle size at ratios of 70% became the same for the remainder of the study.

Each biochar particle size had several ratios, without limestone amendment, that led to a substrate pH appropriate for container-grown plants. Additionally, several biochar-containing substrates were similar to the pH values and trend of the control over time. One specific substrate, 30% BC_{10}, was the same as the control for the first nine weeks before leveling off at a slightly higher pH (Fig. 2.3).

Electrical conductivity values for all substrates were between 0.4 and 0.8 $mS \cdot cm^{-1}$, which reflected levels in local tap water (data not presented). No trends in electrical conductivity were observed based on particle size or biochar ratio.

Physical properties

Total porosity of substrates containing biochar decreased with increasing amounts of all sizes of biochar (Table 2.1). Within biochar-ratio treatments, decreasing particle size increased total porosity. Substrates with 20% BC_6, 20% BC_{10}, 20% BC_{20}, and 30% BC_{20} had greater total porosity than the control. Substrates with 30% BC_{10} and 40% BC_{20} were not different from the control, and all remaining substrates had less total porosity than the control. All biochar sizes had greater total porosity than perlite (Table 2.1).

Container capacity decreased as the amount of biochar increased (Table 2.1). Within biochar-ratio treatments, container capacity increased with decreasing biochar particle size. A substrate with 20% BC_{20} had greater container capacity than the control, whereas 20% BC_6, 20% and 30% BC_{10}, and 30% and 40% BC_{20} were not different from the control substrate. Container capacity of the remaining substrates was less than the control. BC_{10} and BC_{20} had greater container capacity than perlite, whereas BC_6 had less container capacity (Table 2.1).

Increasing amounts of BC_6 resulted in increased air-filled pore space (Table 2.1). A substrate with 30% BC_{10} had less air space than the remaining BC_{10} substrates. All BC_{20}

substrates had the same air space. Within biochar-ratio treatments, air space decreased as biochar size decreased. All BC_6 substrates, 20% BC_{10}, and 40% BC_{10} had greater air space than the control. The remaining substrates were not different from the control substrate. BC_6 had the greatest air space, perlite and BC_{10} were not different, and BC_{20} had the least air space (Table 2.1).

Bulk density increased with an increasing amount of biochar in the substrate (Table 2.1). All biochar-containing substrates tested had bulk densities greater than the commercial substrate. The bulk density of this type of biochar was more than twice the bulk density of the perlite used in this study.

Discussion

Biochar can replace perlite in commercial greenhouse soilless substrates. Without limestone amendment, several biochar ratios provided a pH value similar to the control substrate. Using biochar as a replacement for perlite eliminates the need for amendment with limestone. All but one substrate tested provided physical properties recommended for use in containers (Arnold Bik, 1983; Boertje, 1984; Bunt, 1988). One biochar-containing substrate, 30% BC_{10}, matched the pH and physical properties of the commercial substrate, with the exception of bulk density.

Substrate pH increased as the amount of biochar increased. After a certain amount of biochar was added to the substrate, a threshold was reached where additional biochar did not increase pH. This threshold also existed where particle size no longer affected pH. This observed limit is at a pH similar to a soil buffered by calcium carbonate. The presence of calcium carbonate equivalents added by the biochar may explain this observation. Because most of the calcium, along with magnesium and potassium, contained in the original plant biomass remains in biochar after pyrolysis (Laird et al., 2010a), calcium carbonates, bicarbonates, or other bases are added to the substrate by the biochar.

Substrate pH also increased as the particle size of biochar decreased. One possible explanation for the particle size effect is the sizes, although from the same source material, may have a different calcium content and therefore different calcium carbonate equivalent. Another potential explanation is biochar proximity to the substrate solution may affect pH. Bases within the biochar particle are closer to the substrate solution in a small particle, therefore causing the increased pH relative to substrates containing larger particles of biochar.

Several biochar-containing substrates had pH values similar to the commercial substrate over time (Fig. 2.3). This shows the capacity of biochar to serve as a liming agent, in addition to its effects on the physical properties. The limestone normally added to soilless substrates can be eliminated when biochar is substituted for perlite. The elimination of limestone amendment alone greatly simplifies the formulation of substrates containing relatively large volumes of sphagnum peat. In addition, biochar could facilitate the adjustment of substrate pH by increasing or decreasing the amount or the size of biochar in the substrate.

There are no standards for physical properties of greenhouse substrates, but several recommendations have been proposed. Minima of 85% total pore space and 45% water-filled pore space have been recommended (Arnold Bik, 1983; Boertje, 1984). All biochar-containing substrates in our study met these minima, except for 40% BC_6, which had 82.4% total porosity. All substrates tested also met the recommendation of Bunt (1988) of at least 10% to 20% air-filled pore space (Table 2.1). Bulk densities of all substrates tested were greater than the commercial substrate. Two substrates, 30% BC_{10} and 40% BC_{20}, were the same as the commercial substrate in total porosity, air space, and container capacity (Table 2.1). In addition, the pH of 30% BC_{10} also was the same as that of the control during the first nine weeks of the study, whereas the pH of 40% BC_{20} was greater.

Based on pH values and the physical properties of each substrate, a ratio of 30% BC_{10} to 70% sphagnum peat seems to be optimum. This substrate was the same as the commercial control in all measures except bulk density, which was greater for 30% BC_{10} (Table 2.1). Bulk density is of particular interest when plants or substrate are shipped, as increased bulk density translates into increased freight costs.

If biofuel production via biomass pyrolysis continues to increase, availability of biochar will increase, likely leading to a decrease in the relative cost of biochar. This, along with the benefits and value-added potential of biochar, may work to defray additional shipping costs associated with increased bulk density. Biochar is a stable form of carbon, and additions of biochar to soil are considered a means of carbon sequestration (Laird, 2008). Marketing plants grown in biochar-containing substrates as a green product that sequesters carbon may allow for larger margins and greater profits for the greenhouse industry.

There is considerable diversity in biochars, and our results are only valid for the specific biochar used in this study. However, there are various commercial sources of hardwood biochar produced by slow pyrolysis, so this and similar products are widely available. The accessibility of this biochar, as well as the particle sizes available, made it a good material for use in this study. Other types of biochar may be suitable for use in substrates, and this research provides a starting point in regard to particle size and ratio. However, the properties of the specific biochar used may affect the substrate pH and physical properties, and other biochars should be tested fully before being adopted into a production program.

Despite the increased bulk density, our results illustrate the potential for biochar to replace perlite in commercial, general-use soilless substrates. Other alternate components, such as Growstones and parboiled fresh rice hulls, are suitable as perlite replacements (Evans, 2011). These components can provide the physical properties needed for plant growth, but do not eliminate the need for amendment with limestone. Additionally, using biochar in substrates potentially adds value to biochar, while creating an opportunity for carbon sequestration (Dumroese et al., 2011). Reports of biochar amendments to soilless substrates resulting in improved plant growth (Graber et al., 2010), biochar-induced systemic resistance to disease (Elad et al., 2010), and increased nutrient retention (Altland and Locke, 2012), combined with our results, make biochar an especially attractive component for greenhouse substrates.

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Tables

Table 2.1. Physical properties of biochar[z], perlite, nine biochar-containing substrates, and a perlite-containing substrate as a control.[y]

Substrate composition[x] (% biochar)		Total porosity (% v/v)	Container capacity (% v/v)	Air space (% v/v)	Bulk density ($g•cm^{-3}$)
BC_6	100	78.8 A[w]	33.8 D	45.0 A	0.252 B
	40	82.4 f[v]	60.9 e	21.5 a	0.164 c
	30	84.6 e	65.7 d	18.9 b	0.140 e
	20	89.0 b	71.4 c	17.6 c	0.123 g
BC_{10}	100	80.3 A	50.3 B	30.0 B	0.247 C
	40	84.9 e	65.2 d	19.6 b	0.168 b
	30	86.7 d	71.2 c	15.5 d	0.146 d
	20	89.1 b	72.5 b	16.6 c	0.123 g
BC_{20}	100	79.0 A	64.7 A	14.2 C	0.280 A
	40	86.0 d	71.8 bc	14.2 e	0.175 a
	30	87.5 c	72.5 b	15.0 de	0.142 e
	20	89.9 a	75.6 a	14.3 e	0.130 f
Perlite[u]		69.7 B	38.0 C	31.7 B	0.100 D
Control[t]		86.4 d	71.8 bc	14.5 de	0.112 h

[z] Hardwood biochar sizes include BC_6 (diameter between 3.36 mm and 1.19 mm), BC_{10} (diameter between 2.38 mm and 0.595 mm), and BC_{20} (diameter between 0.841 mm and 0.420 mm).

[y] Physical properties determined using 7.6-cm tall aluminum porometers with 347.5 cm^3 volume.

[x] Substrate composition indicates percentage of biochar, with balance sphagnum peat.

[w] Component means within a column followed by the same uppercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

[v] Substrate means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

[u] 100% perlite (Therm-O-Rock East, Inc., New Eagle, PA).

[t] Control substrate was a standard commercial soilless substrate (Sunshine LC1, Sun Gro Horticulture, Agawam, MA).

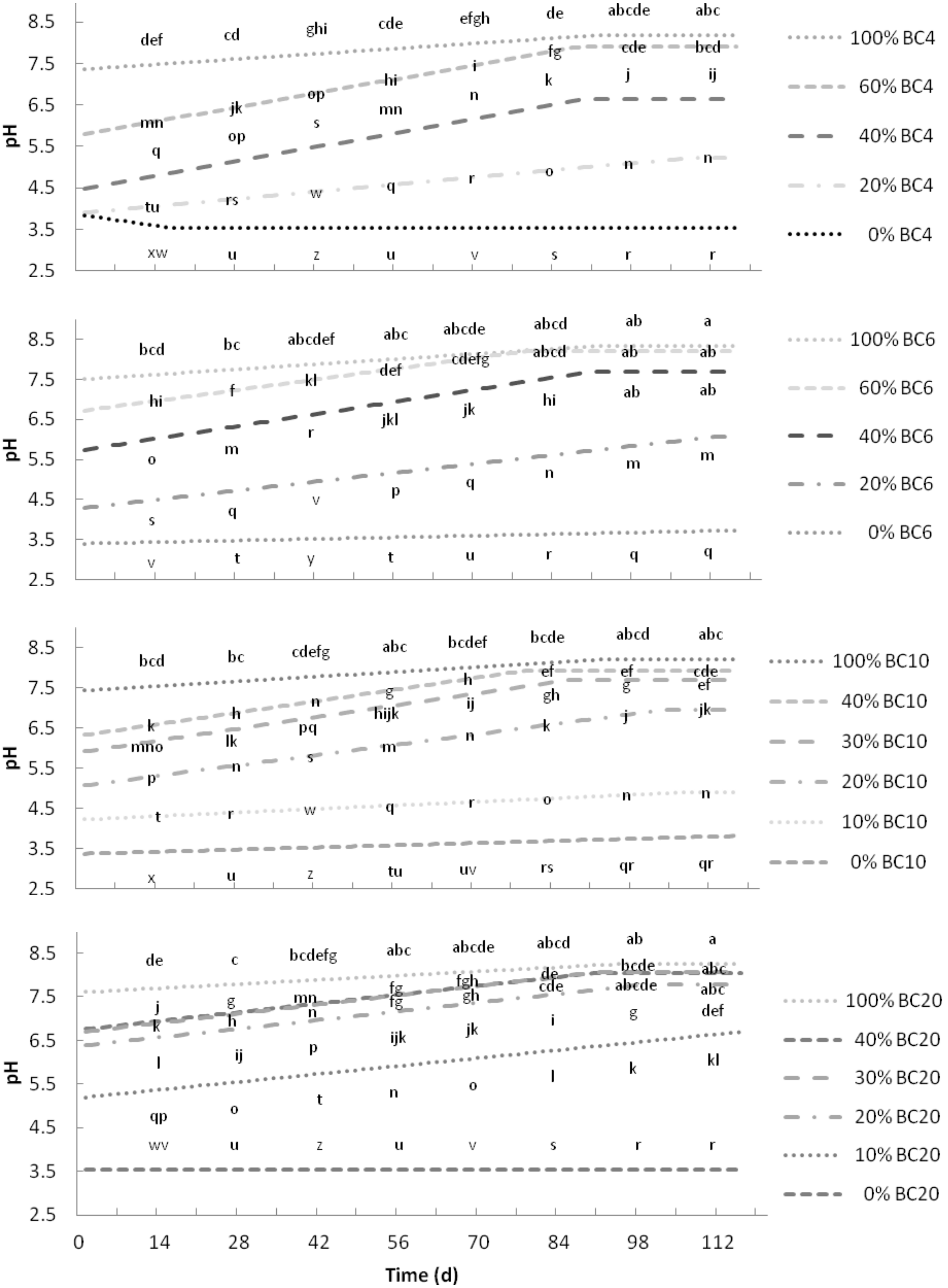
Figures

Fig. 2.1. pH values over time of four sizes of hardwood biochar blended with sphagnum peat by volume. The four sizes of biochar are BC_4 (diameter between 6.35 mm and 2.38 mm), BC_6 (diameter between 3.36 mm and 1.19 mm), BC_{10} (diameter between 2.38 mm and 0.595 mm), and BC_{20} (diameter between 0.841 mm and 0.420 mm). Each biochar size is represented by a selection of ratios to illustrate the pH increase due to biochar amount, and ratios that overlapped the 100% biochar treatments were omitted. Additionally, every other ratio of BC_4 and BC_6 was omitted, as these ratios fell between the others. Dashed lines indicate predicted values based on regression equations. Predicted values were compared at 14-day intervals and lines with the same letter are not different at that time according to Fisher's least significant difference test ($P \leq 0.05$).

Fig. 2.2. pH values over time of four sizes of biochar blended with sphagnum peat at 20:80 biochar:sphagnum peat by volume. The four sizes of biochar are BC_4 (diameter between 6.35 mm and 2.38 mm), BC_6 (diameter between 3.36 mm and 1.19 mm), BC_{10} (diameter between 2.38 mm and 0.595 mm), and BC_{20} (diameter between 0.841 mm and 0.420 mm). This ratio of biochar is shown to illustrate the pH increase due to particle size. Dashed lines indicate predicted values based on regression equations. Predicted values were compared at 14-day intervals and lines with the same letter are not different at that time according to Fisher's least significant difference test ($P \leq 0.05$).

Fig. 2.3. pH values over time of 20%, 30%, and 40% BC_{10}, 100% sphagnum peat (0% BC_{10}), and a commercial, general-use soilless substrate (Sunshine LC1, Sun Gro Horticulture, Agawam,

MA). The percentages indicate the amount of BC_{10} blended by volume with sphagnum peat. Four sizes of biochar were tested and each size had two or three ratios that followed the pH values and trend of the control over time. The peat and biochar mixes had no limestone added, whereas LC1 is amended with limestone. The three ratios of BC_{10} are used as an example to represent the other sizes of biochar evaluated. Dashed lines indicate predicted values based on regression equations. Predicted values were compared at 14-day intervals and lines with the same letter are not different at that time according to Fisher's least significant difference test ($P \leq 0.05$).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14
28
42
56
70
84
98
112
2.5
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7.5
8.5
100% BC4
60% BC4
40% BC4
20% BC4
0% BC4
def cd ghi cde efgh de abcde abc
fg cde bcd
i j ij
hi k
op n
jk
mn mn
s
q op
n n
o
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rs
tu
xw u z u v s r r
100% BC6
60% BC6
40% BC6
20% BC6
0% BC6
bcd bc abcdef abc abcde abcd ab a
cdefg abcd ab ab
def
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hi hi ab ab
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100% BC10
40% BC10
30% BC10
20% BC10
10% BC10
0% BC10
bcd bc cdefg abc bcdef bcde abcd abc
ef ef cde
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ij gh
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h hijk jk
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pq k
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x u z tu uv rs qr qr
100% BC20
40% BC20
30% BC20
20% BC20
10% BC20
0% BC20
de c bcdefg abc abcde abcd ab a
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mn fg gh
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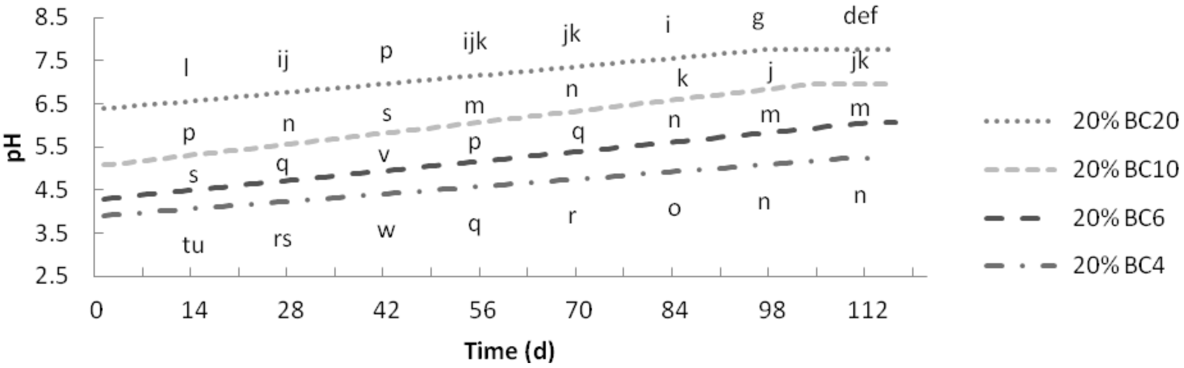
(Fig. 2.1)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112
Time (d)
20% BC20
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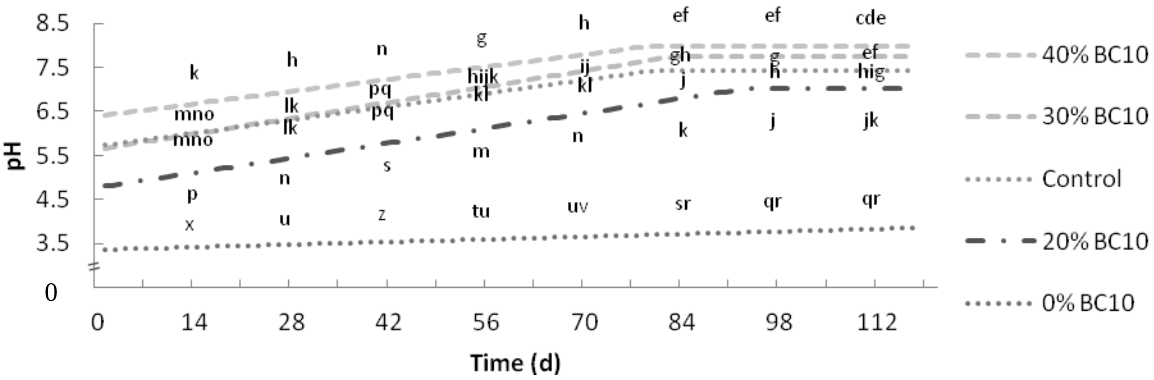
(Fig. 2.2)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pH
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Time (d)
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Control
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(Fig. 2.3)

CHAPTER 3. PLANT GROWTH SHOWS BIOCHAR CAN REPLACE PERLITE IN GREENHOUSE SUBSTRATES

A paper to be submitted to *HortScience*

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Abstract

Biochar is a solid, carbonaceous coproduct of the pyrolysis process used for biofuel production, and it is an excellent means of carbon sequestration. Hardwood biochar provides appropriate physical and chemical properties when replacing perlite and limestone in sphagnum peat-based soilless substrates. Our objectives were to demonstrate appropriate plant growth in biochar-containing substrates and to evaluate the growth of seven crops in these substrates. We obtained three sizes of hardwood biochar, and each size was blended with sphagnum peat in ratios of 20:80, 30:70, and 40:60 biochar:sphagnum peat, resulting in nine substrates. Substrates that contained biochar were not amended with limestone and did not receive any nutrients before transplanting. Plants grown in biochar-containing substrates were compared to plants grown in a commercial substrate that contained sphagnum peat, perlite, and limestone, Sunshine LC1. Plants grew in each substrate for 27 or 35 days. Electrical conductivity and pH were measured 14 days after transplanting and at the end of each trial. Results varied among trials and crops grown. Many biochar-based substrates produced plants with shoot dry mass greater than or

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[2] Primary researcher and author.

[3] Co-Major Professor.

equal to the control. The pH of several biochar-based substrates was elevated beyond levels normally considered detrimental to plant health, but the growth, development, and health of these plants seemed normal and no nutrient deficiencies were observed. Our results demonstrate substrates containing biochar as a replacement for perlite and limestone can successfully be used for plant production in greenhouse soilless substrates.

Introduction

Biochar is the term for charcoal intended for use as a soil amendment. It is a carbonaceous residue generated by heating biomass in the absence or near-absence of oxygen, a process known as pyrolysis. This thermochemical process transforms organic compounds into a vapor phase, which remains as syngas or is condensed into bio-oil, and the solid biochar residue. If use of biomass pyrolysis to produce renewable fuels proves economical, there likely will be large quantities of the biochar coproduct available for other applications (Laird et al., 2009).

Reports of biochar amendments to soil resulting in improved plant growth and enhanced soil quality (Steiner et al., 2007; Laird et al., 2010) have attracted substantial research interest in biochar. Furthermore, biochar additions to soil also are considered a means of sequestering carbon (Laird, 2008). Application of biochar to agronomic soils can enhance soil quality and sequester carbon, but a lack of short-term return on investment and potential challenges including transport, handling, and application of biochar to the field may hinder widespread agricultural use of biochar (Laird, 2008). Because biochar production diverts a raw material that potentially could be turned into fuel, energy companies have little incentive to produce biochar (Laird, 2008). However, the potential for horticultural use of biochar exists in soilless substrates used for container production of greenhouse crops. Using biochar in substrates potentially adds value to biochar, while creating an opportunity for carbon sequestration (Dumroese et al., 2011).

Biochar previously has been evaluated in soilless substrates. Santiago and Santiago (1989) discussed a system for growing plants outdoors in Malaysia using processed charcoal chips and chunks as a container substrate. This specialized system was tailored to the rainy climate, and plants grew well as long as nutrition was provided via resin-coated, slow-release fertilizers. Dumroese et al. (2011) studied the use of pelleted biochar in nursery container substrates. The optimal substrate, which contained 75% peat moss and 25% biochar pellets, was found suitable for production of containerized nursery plants. Tian et al. (2012) found improved growth of *Calathea rotundifola* cv. Fasciata Korn in biochar made from urban green waste mixed with peat in equal parts, compared to growth in peat or green waste biochar alone.

Biochar also has been studied as an amendment in soilless substrates, and it provided improved plant growth as well as biochar-induced systemic resistance to disease (Elad et al., 2010; Graber et al., 2010). Altland and Locke (2012) demonstrated that additions of biochar up to 10% by volume decreased peak nitrate and phosphate leaching by slowing their release over time. This suggests nitrate could be applied less frequently due to the capacity of biochar to hold nitrate and release it to the plant roots slowly. Additionally, phosphate and K applications could be reduced because these nutrients are present in biochar and are released over time (Altland and Locke, 2012). Field studies also have indicated the fertilizer potential of biochar (Glaser et al., 2002).

We have evaluated the capacity of hardwood biochar to replace perlite in commercial greenhouse soilless substrates, and we determined biochar can provide the pH and physical properties needed for use in greenhouse containers (Northup et al., 2013). The objectives of this study were to evaluate plant growth in substrates containing hardwood biochar as a replacement for perlite and to evaluate the growth of several species commonly produced in containers in greenhouses.

Materials and Methods

Substrate preparation

Three sizes of prescreened hardwood biochar were obtained from a commercial charcoal-production facility (Royal Oak Charcoal, Roswell, GA). The three sizes of biochar were BC_6 (largest), BC_{10}, and BC_{20} (smallest). Particles of BC_6, BC_{10}, and BC_{20} passed through sieves with openings of 3.36 mm, 2.38 mm, and 0.841 mm, respectively, and were retained on sieves with openings of 1.19 mm, 0.595 mm, and 0.420 mm, respectively. Each biochar size was blended with sphagnum peat (Conrad Fafard, Inc., Agawam, MA), by volume, at rates of 20%, 30%, and 40% biochar, resulting in nine biochar-containing substrates. Components were measured, layered in a rotary concrete mixer, and blended for 1 min at 45 revolutions per minute. After mixing, the substrates were stored dry in plastic bags until use. For initial wetting of biochar substrates about one gallon of dry substrate was placed into a two-gallon plastic zip bag with 350 mL of 1500 ppm Matador liquid soil surfactant (ENP, Inc., Mendota, IL) and allowed to saturate for one to four days. A standard commercial soilless substrate composed of sphagnum peat and perlite, and amended with dolomitic limestone and a starter fertilizer charge (Sunshine LC1, Sun Gro Horticulture, Agawam, MA), was used as a control.

Growth

Single plants of ‘Bonanza Orange’ marigold (*Tagetes patula* L. French M.), ‘Madness Burgundy’ petunia (*Petunia* ×*hybrida* Hort. Vilm.-Andr.), ‘Super Elfin XP White’ impatiens (*Impatiens walleriana* Hook. f.), ‘Marathon’ broccoli (*Brassica oleracea* L. Italica group), and ‘California Wonder’ pepper (*Capsicum annuum* L.) were transplanted, upon the expansion of second set of true leaves, into 10.2-cm pots with a volume of 601 cm^3. 'Super Sweet 100' tomato (*Lycopersicon esculentum* Mill.) and 'Straight Eight' cucumber (*Cucumis sativus* L.) were transplanted into 12.7-cm pots with a volume of 1,090 cm^3. All plants were propagated from seed. There were five replications for each substrate and control. Plants grew in a greenhouse with night temperatures ranging from 21 to 26 °C (22.5 °C average) and day temperatures ranging from 21 to 33 °C (25.5 ° C average). Supplemental lighting was utilized as needed to maintain irradiance of 380 to 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 14 hours daily. Plants were fertilized at alternate irrigations with 150 mg/L N (16.6N-5P-16.3K, Peters Excel Multi-Purpose (75%) plus CalMag (25%), Everris International B.V., The Netherlands) and held on greenhouse benches for 35 days after transplanting, 27 days for cucumber. At the end of the growing period, plants were harvested for shoot and root dry mass. Shoots were severed at the soil surface and dried in a 67 °C oven for 72 hours. Roots were washed for determination of dry mass but root hairs had entered biochar pores and the material was very difficult to wash away. Further washing caused loss of root mass, and although successful at removing larger particles of biochar, washing did not result in removal of smaller particles. Due to inconsistent washing and loss of root mass, dry mass of roots is not reported.

pH and electrical conductivity

Substrate pH and electrical conductivity (EC) were recorded 14 and 35 days after transplanting, except for cucumber which were recorded at 14 and 27 days. The PourThru extraction method described by Cavins et al. (2000), and a HANNA combination meter (HI 9811, HANNA Instruments, Inc., Woonsocket, RI) were used to determine pH and electrical conductivity. All five replications for each treatment were measured on these days.

Data analysis

This experiment was a randomized complete block design. Blocks were repeated in the same greenhouse over time, and time was significant so blocks were evaluated separately and from this point will be referred to as trials. Data for each trial were analyzed using Statistical Analysis System software version 9.3 (SAS Institute Inc., Cary, NC, 2010). Analysis of variance was conducted to test for growth differences between substrates and for differences between pH and EC values. Treatment means were compared with Fisher's least significant difference test at $P \leq 0.05$.

Results

Impatiens shoot dry mass

Throughout all trials, impatiens grown in all biochar-containing substrates produced shoot dry mass equal to or greater than the control (Table 3.1). In trial 1, impatiens grown in 20% BC_{10} and 30% BC_{10} had greater shoot dry mass compared to the control, and all remaining substrates were the same. In trial 2, all biochar substrates produced plants with greater dry mass than the control (Table 3.1). Trial 3 impatiens in all BC_{10} substrates, 20% BC_{20}, and 30% BC_{20} had greater dry mass than the control, and all remaining substrates were the same (Table 3.1).

Marigold shoot dry mass

All BC_{10} and BC_{20} substrates produced marigold shoot dry mass equal to the control in trial 1(Table 3.2). All BC_6 substrates had less shoot dry mass in this trial. Marigold dry mass in trial 2 was the same as the control in all substrates except 20% BC_{10}, 20% BC_6, and 40% BC_6, which had less dry mass (Table 3.2). Trial 3 marigolds grown in 40% BC_{10} and 30% BC_{20} had greater dry mass compared to the control, and all remaining substrates were not different from the control substrate (Table 3.2).

Petunia shoot dry mass

In trial 1, all BC_{10} and BC_{20} substrates produced petunia shoot dry mass equal to the control, whereas all petunias grown in BC_6 substrates were less than the control (Table 3.3). Trial 2 results followed the same trend except for 30% BC_{10}, which had greater dry mass compared to the control, but was the same as the remaining BC_{10} and BC_{20} substrates (Table 3.3). There was no third petunia trial due to lack of seedling uniformity.

Broccoli shoot dry mass

All BC_{10} and BC_{20} substrates produced broccoli shoot dry mass equal to the control in trial 1, and all broccoli grown in BC_6 substrates were less than the control (Table 3.4). Trial 2 broccoli dry mass was the same as the control in 20% BC_{10}, 30% BC_{20}, and 40% BC_{20} (Table 3.4). The remaining substrates produced less broccoli dry mass compared to the control. Broccoli grown in 40% BC_{10}, 30% BC_{20}, and 40% BC_{20} had dry mass greater than the control in trial 3, whereas broccoli grown in 20% BC_6 had less dry mass. The remaining substrates produced dry mass equal to the control (Table 3.4).

Cucumber shoot dry mass

Dry mass of cucumber grown in 20% BC_{20} and 40% BC_{20} was equal to the control in trial 1 (Table 3.5). All remaining substrates in this trial produced cucumber with less dry mass. In trial 2, all biochar substrates produced less cucumber dry mass than the control (Table 3.5). Cucumber growth in trial 3 was the same as the control in all BC_{10} substrates as well as 30% BC_{20} and 40% BC_{20}. The remaining substrates produced less cucumber dry mass (Table 3.5).

Pepper shoot dry mass

Trial 1 pepper grown in all BC_{20} substrates and 20% BC_{10} had dry mass equal to the control, and all remaining substrates produced less dry mass (Table 3.6). In trail 2, all peppers grown in biochar substrates had greater dry mass than the control except for 20% BC_6, which was the same (Table 3.6). Peppers grown in all BC_{20} substrates, 30%BC_{10}, and 40% BC_{10} had greater dry mass compared to the control in trial 3. 20% BC_6 had less dry mass compared to the control and all remaining substrates were the same as the control (Table 3.6).

Tomato shoot dry mass

Shoot dry mass of tomato grown in 20% BC_{20} and 40% BC_{20} was not different from the control in trial 1, and all remaining substrates produced less dry mass than the control (Table 3.7). In trial 2 all biochar substrates produced less tomato dry mass than the control (Table 3.7). This trend continued in trial 3, with all biochar substrates less than the control.

Substrate pH and EC

For all crops in all trials, except for impatiens in trial 1, EC values recorded 2 weeks after transplant were greater in the control compared to all other substrates (Tables 3.1 to 3.7). In all trials of tomato, pepper, broccoli, and marigold, and cucumber trial 3 and impatiens trial 2, several substrates had EC values similar to the control by the end of the experiment. Within each size of biochar, increasing the amount of biochar resulted in increased substrate pH (Tables 3.1 to 3.7). At the same volume of biochar in the substrate, smaller particle size generally led to increased substrate pH.

Discussion

Substrates containing biochar can grow plants as well as or better than the control substrate used in this experiment. Without limestone amendment, biochar blended with sphagnum peat provided pH values that allowed for normal plant growth. Even with lower initial EC values, biochar-containing substrates produced plants with equal or greater shoot dry mass compared to plants grown in the control substrate.

Growth in biochar-containing substrates varied among the crops tested. In several instances, such as tomato in trials 2 and 3, growth was greatest in the control substrate. The biochar size and ratio that led to the greatest dry mass varied among crops. This was expected, as there is no single soilless substrate that is optimal for all crops in all situations. Additionally, field investigations indicate the amount of biochar to add for optimum plant growth varies and may have to be determined for each plant (Glaser et al., 2002).

Our previous results indicated biochar blended with sphagnum peat eliminates the need for amendment with limestone (Northup et al., 2013). Our experiments demonstrate biochar eliminates the need for limestone amendment and plants can grow normally in these substrates. In some cases, plants seemed to be healthy and growing normally at a pH typically considered detrimental to the health of the plant. An example of this is trial 2 petunia grown in 40% BC_{20}, which had a mean pH of 7.6 (Table 3.3). According to Cavins et al. (2000), the target pH range for petunia is 5.4 to 5.8, with management decisions suggested before pH exceeds 6.0. Our petunias grew at a much greater pH, and they did not show noticeable indications of an elevated pH. It is important to note this was an observation, and no nutrient testing was conducted during these experiments. The potential to achieve normal plant growth at an elevated pH when grown in biochar-containing substrates is an exciting possibility that requires further testing.

EC is an indication of fertilizer concentration (Nelson, 2012). The initial EC measurement of each substrate was taken 14 days after transplanting, and it was greater in the control in every case except impatiens trial 1(Tables 3.1 to 3.7). This was due to the starter fertilizer charge contained in the control substrate. Despite this advantage, dry mass was often equal to or greater in plants grown in substrates containing biochar. We hypothesize this is due to the combination of the ability of biochar to hold and slowly release nutrients in a soilless substrate (Altland and Locke, 2012) and the potential for biochar itself acting as a fertilizer (Glaser et al., 2002).

Biochar is a suitable component for general-use, sphagnum peat-based soilless substrates. Biochar in substrates has the potential to reduce nutrient applications (Altland and Locke, 2012) as well as increase the value of biochar and create carbon sequestration opportunities (Dumroese et al., 2011). Reduced fertilizer applications and eliminated limestone amendments, combined with the value-added potential of selling plants grown in biochar, may result in greater profits for greenhouse growers. Additional benefits may exist if biochar is found to increase the pH range in which high-quality plants can be grown. However, this aspect of using biochar in substrates requires additional evaluation.

There is considerable diversity in biochars, and our results are only valid for the specific biochar used in this study. However, there are various commercial sources of hardwood biochar produced by slow pyrolysis, so this and similar products are widely available. The accessibility of this biochar, as well as the particle sizes available, made it a good material for use in this study. Other types of biochar may be suitable for use in substrates, and this research provides a starting point in regard to particle size and ratio. However, the properties of the specific biochar used may affect the substrate pH and physical properties, and other biochars should be tested fully before being adopted into a production program.

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Tables

Table 3.1. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar[z]-containing substrates and a commercial, general-use soilless substrate[y] used to grow impatiens.

Substrate composition[x]		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} (mS•cm^{-1})	EC_{35} (mS•cm^{-1})
			Trial 1			
Control[y]		3.4 bcd[w]	6.4 b	6.7 a	1.59 a	0.81 b
BC_{20}	40	3.6 ab	6.5 a	6.6 a	1.49 ab	0.66 cd
	30	3.6 abc	6.0 c	6.1 c	1.43 abc	0.63 cd
	20	3.5 abcd	5.2 ef	5.1 ef	1.30 abc	0.65 cd
BC_{10}	40	3.6 ab	6.5 a	6.4 b	1.34 abc	0.67 cd
	30	3.7 a	5.6 d	5.3 d	1.22 bc	0.66 cd
	20	3.7 a	4.7 g	4.4 g	1.21 bc	0.63 cd
BC_6	40	3.3 cd	5.1 f	5.1 f	1.16 c	0.61 d
	30	3.3 bcd	4.3 h	4.1 h	1.16 c	0.63 cd
	20	3.3 bcd	3.9 i	3.7 i	1.19 c	0.77 ab
			Trial 2			
Control[y]		3.2 d	6.3 b	6.8 b	1.51 a	0.82 cde
BC_{20}	40	5.0 a	6.7 a	7.0 a	1.17 b	0.92 ab
	30	4.7 abc	5.5 d	5.7 e	1.03 c	0.88 abcd
	20	5.0 a	4.8 f	4.8 g	0.93 cde	0.84 bcde

BC$_{10}$	40	4.6 abc	6.2 b	6.5 c	1.02 c	0.92 ab
	30	4.8 ab	5.7 c	6.0 d	0.95 cd	0.89 abc
	20	5.1 a	4.6 g	4.6 h	0.94 cde	0.93 a
BC$_{6}$	40	4.3 bc	5.0 e	5.2 f	0.81 e	0.80 de
	30	4.2 bc	4.5 h	4.5 h	0.83 de	0.88 abc
	20	4.5 abc	4.0 i	3.8 i	0.90 cde	0.96 a
			Trial 3			
Control^{y}		3.5 e	6.2 b	*^{v}	1.57 a	*
BC$_{20}$	40	3.9 cde	6.7 a	*	0.97 b	*
	30	4.3 abc	6.3 b	*	0.93 bc	*
	20	4.1 bcd	4.6 f	*	0.83 bcde	*
BC$_{10}$	40	4.7 a	6.6 a	*	0.86 bcd	*
	30	4.0 cd	5.7 c	*	0.86 bcd	*
	20	4.6 ab	4.5 g	*	0.82 cde	*
BC$_{6}$	40	3.7 de	5.0 e	*	0.71 ef	*
	30	3.9 cde	4.2 h	*	0.71 f	*
	20	3.5 e	3.8 i	*	0.76 def	*

[z] Hardwood biochar sizes include BC$_{6}$ (diameter between 3.36 mm and 1.19 mm), BC$_{10}$ (diameter between 2.38 mm and 0.595 mm), and BC$_{20}$ (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher’s least significant difference test ($P \leq 0.05$, n = 5).

[v] A * indicates data were not collected.

Table 3.2. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar[z]-containing substrates and a commercial, general-use soilless substrate[y] used to grow marigold.

Substrate composition[x]		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} ($mS \cdot cm^{-1}$)	EC_{35} ($mS \cdot cm^{-1}$)
			Trial 1			
Control[y]		4.4 ab[w]	6.6 b	6.8 b	1.83 a	0.78 a
BC_{20}	40	4.4 a	6.9 a	7.1 a	1.06 b	0.74 a
	30	4.3 ab	6.1 c	6.4 c	1.03 bc	0.77 a
	20	4.2 abc	4.7 f	5.4 e	0.86 d	0.59 b
BC_{10}	40	4.3 ab	6.6 b	6.8 b	0.97 bcd	0.75 a
	30	4.3 ab	5.7 d	5.9 d	0.86 d	0.64 b
	20	4.1 abcd	4.7 f	5.2 f	0.86 d	0.63 b
BC_6	40	3.7 de	4.9 e	5.4 e	0.90 cd	0.62 b
	30	3.8 cd	4.2 g	4.7 g	0.85 d	0.61 b
	20	3.3 e	3.9 h	4.0 h	0.90 cd	0.60 b
			Trial 2			
Control[y]		5.4 ab	6.6 b	6.6 b	1.24 a	0.89 a
BC_{20}	40	5.6 ab	6.8 a	7.0 a	0.95 b	0.86 a
	30	5.9 a	6.3 c	6.4 c	0.85 bc	0.86 a
	20	5.3 abc	4.9 f	4.9 f	0.70 de	0.54 de
BC_{10}	40	5.6 ab	6.6 b	6.6 b	0.80 cd	0.74 b

	30	5.3 abc	5.8 d	5.7 d	0.83 c	0.71 bc
	20	4.5 d	4.4 g	4.5 g	0.71 de	0.58 de
BC$_{6}$	40	4.7 cd	4.9 f	5.2 e	0.71 de	0.59 de
	30	5.1 bcd	4.2 h	4.3 h	0.70 de	0.53 de
	20	4.6 d	3.8 i	3.8 i	0.67 e	0.51 e

Trial 3

Control[y]		4.5 cd	6.1 c	6.5 b	1.70 a	0.72 b
BC$_{20}$	40	4.8 bc	6.7 a	6.9 a	1.11 b	0.82 a
	30	5.1 ab	6.0 d	6.4 c	1.08 b	0.84 a
	20	4.9 bc	4.8 g	5.1 f	0.86 cd	0.60 c
BC$_{10}$	40	5.5 a	6.3 b	6.4 bc	0.92 c	0.87 a
	30	4.9 bc	5.5 e	5.7 d	0.85 cde	0.70 b
	20	4.7 bcd	4.5 h	4.8 g	0.76 ef	0.60 c
BC$_{6}$	40	4.5 cd	5.0 f	5.2 e	0.77 def	0.66 bc
	30	4.7 bcd	4.4 i	4.5 h	0.73 f	0.64 bc
	20	4.2 d	3.9 j	4.0 i	0.84 cde	0.57 c

[z] Hardwood biochar sizes include BC$_{6}$ (diameter between 3.36 mm and 1.19 mm), BC$_{10}$ (diameter between 2.38 mm and 0.595 mm), and BC$_{20}$ (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

Table 3.3. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar[z]-containing substrates and a commercial, general-use soilless substrate[y] used to grow petunia.

Substrate composition[x]		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} ($mS\cdot cm^{-1}$)	EC_{35} ($mS\cdot cm^{-1}$)
Trial 1						
Control[y]		2.4 a[w]	6.1 c	6.8 b	1.89 a	0.98 a
BC_{20}	40	2.3 ab	6.8 a	7.0 a	1.08 bc	0.75 b
	30	2.4 ab	5.9 d	6.0 c	1.03 bc	0.72 b
	20	2.3 abc	4.8 f	4.8 e	0.91 cde	0.63 b
BC_{10}	40	2.3 ab	6.5 b	6.7 b	1.12 b	0.75 b
	30	2.5 a	5.7 e	5.7 d	0.87 e	0.65 b
	20	2.2 abc	4.2 h	4.2 f	0.96 cde	0.68 b
BC_6	40	1.8 de	4.6 g	4.9 e	0.93 cde	0.63 b
	30	2.1 bcd	4.0 i	3.9 g	0.94 cde	0.68 b
	20	1.7 e	3.6 j	3.5 h	1.01 bcd	0.65 b
Trial 2						
Control[y]		2.8 bc	6.8 b	6.5 c	0.92 a	1.30 a
BC_{20}	40	2.9 abc	7.2 a	7.6 a	0.67 bc	1.12 b
	30	3.1 a	6.4 c	6.6 c	0.64 bcd	0.95 c
	20	2.9 abc	5.0 e	5.6 e	0.63 cd	0.79 d
BC_{10}	40	2.9 ab	6.5 c	7.0 b	0.63 cd	0.93 c

	30	2.8 abc	5.6 d	6.1 d	0.65 bc	0.94 c
	20	3.0 ab	4.7 f	5.1 f	0.63 cd	0.76 d
BC_6	40	2.3 d	4.8 ef	5.4 e	0.60 cd	0.79 d
	30	2.3 d	4.2 g	4.5 g	0.57 d	0.80 d
	20	2.2 d	3.9 h	4.1 h	0.65 bc	0.86 cd

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[z] Hardwood biochar sizes include BC_6 (diameter between 3.36 mm and 1.19 mm), BC_{10} (diameter between 2.38 mm and 0.595 mm), and BC_{20} (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

Table 3.4. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar[z]-containing substrates and a commercial, general-use soilless substrate[y] used to grow broccoli.

Substrate composition[x]		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} (mS•cm^{-1})	EC_{35} (mS•cm^{-1})
		Trial 1				
Control[y]		8.7 a[w]	6.7 b	6.9 b	1.17 a	1.09 a
BC_{20}	40	8.2 a	7.0 a	7.2 a	0.69 bcd	1.01 ab
	30	8.5 a	6.1 c	6.4 d	0.62 cde	0.58 cd
	20	7.6 ab	4.9 f	5.5 f	0.60 de	0.71 ef
BC_{10}	40	8.7 a	6.6 b	6.7 c	0.72 b	0.92 bc
	30	8.4 a	5.5 d	5.8 e	0.56 e	0.80 cde
	20	7.9 ab	4.6 g	5.2 g	0.60 de	0.65 f
BC_6	40	6.9 bc	5.3 e	5.9 e	0.60 de	0.73 def
	30	7.0 bc	4.2 h	4.7 h	0.69 bcd	0.67 ef
	20	6.2 c	3.8 i	4.2 i	0.71 bc	0.71 ef
		Trial 2				
Control[y]		6.8 a	6.5 c	6.6 b	1.36 a	1.68 ab
BC_{20}	40	6.3 abc	7.0 a	7.1 a	0.67 bcd	1.92 a
	30	6.6 ab	6.1 d	6.3 c	0.59 de	1.96 a
	20	5.8 cd	4.6 g	5.0 f	0.59 de	1.20 bc
BC_{10}	40	6.0 bcd	6.7 b	7.0 a	0.62 cde	1.70 ab

	30	5.8 cd	5.6 e	6.0 d	0.56 e	1.67 ab
	20	6.1 abcd	4.3 h	4.6 g	0.61 cde	1.12 bc
BC_6	40	4.8 e	4.8 f	5.3 e	0.58 de	0.81 c
	30	5.5 de	4.0 i	4.5 h	0.61 cde	1.04 bc
	20	5.0 e	3.6 j	3.9 i	0.69 bc	0.88 c

Trial 3

Control[y]		8.3 bc	6.1 c	6.7 c	1.99 a	0.92 ab
BC_{20}	40	9.4 a	6.7 a	7.2 a	0.94 b	1.03 a
	30	9.4 a	6.0 d	6.5 d	0.88 bc	0.91 abc
	20	9.0 ab	4.9 f	5.4 g	0.88 bc	0.81 bcde
BC_{10}	40	9.3 a	6.4 b	6.9 b	0.87 bc	0.99 a
	30	9.0 ab	5.6 e	6.2 e	0.86 bc	0.93 ab
	20	8.5 ab	4.7 g	5.3 h	0.82 bc	0.79 cde
BC_6	40	8.1 bc	4.9 f	5.7 f	0.74 c	0.86 bcd
	30	7.4 cd	4.5 h	5.0 i	0.75 c	0.79 cde
	20	6.5 d	3.9 i	4.4 j	0.83 bc	0.72 e

[z] Hardwood biochar sizes include BC_6 (diameter between 3.36 mm and 1.19 mm), BC_{10} (diameter between 2.38 mm and 0.595 mm), and BC_{20} (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

Table 3.5. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar[z]-containing substrates and a commercial, general-use soilless substrate[y] used to grow cucumber.

Substrate composition[x]		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} (mS•cm^{-1})	EC_{35} (mS•cm^{-1})
		Trial 1				
Control[y]		7.0 a[w]	6.6 b	6.4 b	1.41 a	1.03 a
BC_{20}	40	6.6 ab	6.9 a	6.6 a	0.65 b	0.70 b
	30	5.6 cd	5.8 d	5.2 d	0.53 c	0.54 cd
	20	6.2 abc	5.0 f	4.8 f	0.51 c	0.50 cd
BC_{10}	40	6.1 bc	6.5 c	6.0 c	0.58 c	0.62 bc
	30	5.6 cd	5.2 e	5.0 e	0.52 c	0.54 cd
	20	5.6 cd	4.2 h	4.4 g	0.50 c	0.50 cd
BC_{6}	40	5.6 cde	4.7 g	4.7 f	0.50 c	0.51 cd
	30	4.8 e	3.9 i	4.2 h	0.49 c	0.49 d
	20	4.9 de	3.6 j	3.8 i	0.49 c	0.51 cd
		Trial 2				
Control[y]		5.9 a	6.5 b	6.3 b	1.33 a	0.96 a
BC_{20}	40	5.1 b	6.8 a	6.5 a	0.76 b	0.75 b
	30	5.1 b	5.4 c	5.3 c	0.66 cd	0.55 c
	20	4.5 b	4.6 e	4.9 e	0.66 bcd	0.52 c
BC_{10}	40	4.5 b	6.5 b	6.4 b	0.69 bcd	0.72 b

	30	4.8 b	5.1 d	5.2 d	0.63 cd	0.55 c
	20	4.7 b	4.2 g	4.5 f	0.65 cd	0.49 c
BC$_6$	40	3.7 c	4.5 f	4.8 e	0.61 cd	0.51 c
	30	2.8 d	3.9 h	4.2 g	0.60 d	0.50 c
	20	3.6 c	3.6 i	3.9 h	0.64 cd	0.49 c
Trial 3						
Control[y]		8.1 a	6.3 b	6.1 a	1.61 a	0.82 a
BC$_{20}$	40	7.4 ab	6.5 a	6.1 a	0.72 bc	0.76 a
	30	7.2 ab	5.5 c	5.3 b	0.69 bcd	0.59 b
	20	6.3 bc	4.6 e	4.5 d	0.70 bcd	0.53 bc
BC$_{10}$	40	7.8 a	6.5 a	6.2 a	0.79 b	0.60 b
	30	7.5 ab	5.1 d	4.8 c	0.71 bcd	0.46 cd
	20	6.9 abc	4.2 g	4.1 f	0.69 bcd	0.44 d
BC$_6$	40	5.8 cd	4.5 f	4.4 e	0.64 d	0.46 cd
	30	5.5 cd	4.0 h	3.9 g	0.65 cd	0.46 cd
	20	4.9 d	3.6 i	3.6 h	0.68 bcd	0.46 cd

[z] Hardwood biochar sizes include BC$_6$ (diameter between 3.36 mm and 1.19 mm), BC$_{10}$ (diameter between 2.38 mm and 0.595 mm), and BC$_{20}$ (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

Table 3.6. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar[z]-containing substrates and a commercial, general-use soilless substrate[y] used to grow pepper.

Substrate composition[x]		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} ($mS•cm^{-1}$)	EC_{35} ($mS•cm^{-1}$)
			Trial 1			
Control[y]		5.9 ab[w]	6.3 b	6.6 b	1.79 a	1.39 b
BC_{20}	40	6.2 a	6.5 a	6.8 a	1.29 bc	1.22 bc
	30	5.9 ab	6.1 c	6.4 c	1.32 bc	1.86 a
	20	5.4 bc	5.6 d	5.9 d	1.17 cd	0.95 cde
BC_{10}	40	5.2 c	6.5 a	6.9 a	1.40 b	1.13 bcd
	30	5.0 c	5.5 d	5.8 d	1.34 bc	1.13 bcd
	20	5.3 c	4.8 f	4.9 f	1.17 cd	1.10 bcd
BC_6	40	4.8 c	5.1 e	5.7 e	1.02 d	0.86 de
	30	5.0 c	4.4 g	4.7 g	1.15 cd	1.03 cde
	20	4.1 d	3.8 h	3.9 h	1.20 bcd	0.79 e
			Trial 2			
Control[y]		2.5 f	6.5 b	6.8 b	1.20 a	1.19 ab
BC_{20}	40	3.3 b	6.8 a	7.2 a	0.96 b	1.25 a
	30	3.3 b	6.0 c	6.4 c	0.81 cd	1.19 ab
	20	3.1 bcd	4.7 e	4.7 e	0.78 d	1.21 ab
BC_{10}	40	3.7 a	6.6 b	6.9 b	0.83 cd	1.14 abc

	30	3.7 a	5.9 d	6.3 c	0.81 cd	1.08 bcd
	20	3.6 a	4.4 f	4.5 e	0.84 cd	1.09 bcd
BC$_{6}$	40	3.0 cde	4.8 e	4.9 d	0.76 d	1.01 cde
	30	2.9 de	4.1 g	4.3 f	0.78 d	0.92 e
	20	2.8 ef	3.8 h	3.9 g	0.75 d	0.97 de

Trial 3

Control[y]		5.2 de	5.9 d	6.9 b	2.18 a	1.19 a
BC$_{20}$	40	6.2 a	6.7 a	7.2 a	1.11 b	1.13 ab
	30	5.8 abc	6.1 c	6.6 c	1.05 bc	0.95 cdef
	20	5.8 bc	4.8 g	5.3 f	0.91 cde	1.01 bcde
BC$_{10}$	40	5.9 ab	6.5 b	6.9 b	0.99 bc	0.98 cdef
	30	5.6 bc	5.6 e	6.1 d	0.94 bcd	1.07 abc
	20	5.5 cd	4.8 gh	5.3 f	1.02 bc	1.02 bcd
BC$_{6}$	40	4.9 ef	5.3 f	5.7 e	0.76 de	0.93 def
	30	5.1 ef	4.7 h	5.0 g	0.75 e	0.87 f
	20	4.7 f	4.1 i	4.2 h	0.94 bcd	0.89 ef

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[z] Hardwood biochar sizes include BC$_{6}$ (diameter between 3.36 mm and 1.19 mm), BC$_{10}$ (diameter between 2.38 mm and 0.595 mm), and BC$_{20}$ (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

Table 3.7. Shoot dry mass and initial (day 14) and final (day 35) pH and electrical conductivity (EC) of nine biochar^{z}-containing substrates and a commercial, general-use soilless substrate^{y} used to grow tomato.

Substrate composition^{x}		Shoot dry mass (g)	pH_{14}	pH_{35}	EC_{14} (mS•cm^{-1})	EC_{35} (mS•cm^{-1})
		Trial 1				
Control^{y}		13.3 a^{w}	6.6 b	7.0 ab	1.51 a	1.55 a
BC_{20}	40	12.1 abc	6.9 a	7.2 a	0.62 bc	1.31 ab
	30	11.7 bcd	5.8 d	6.4 c	0.59 c	1.15 bc
	20	12.5 ab	4.5 g	6.2 cd	0.57 c	1.04 bc
BC_{10}	40	11.3 cde	6.4 c	6.8 b	0.56 c	1.35 ab
	30	12.0 bc	5.3 e	6.1 d	0.54 c	1.34 ab
	20	11.5 bcde	4.3 h	5.8 e	0.60 c	1.15 bc
BC_{6}	40	10.5 e	4.8 f	5.9 e	0.56 c	1.31 ab
	30	11.1 cde	4.0 i	5.2 f	0.57 c	1.03 bc
	20	10.7 de	3.7 j	5.0 g	0.64 bc	0.91 c
		Trial 2				
Control^{y}		8.1 a	6.3 b	6.4 c	1.51 a	1.45 a
BC_{20}	40	7.0 b	6.3 b	6.6 b	0.72 bcd	1.24 ab
	30	6.8 b	5.3 c	5.5 d	0.68 cd	1.19 bc
	20	6.7 b	4.3 d	4.3 f	0.65 cde	0.90 de
BC_{10}	40	7.1 b	6.6 a	6.7 a	0.63 cde	0.96 cde

	30	6.6 bc	5.4 c	5.7 d	0.61 de	1.01 bcd
	20	6.2 cd	4.1 e	4.3 f	0.64 cde	0.78 de
BC_6	40	5.5 e	4.3 d	4.8 e	0.57 e	0.75 de
	30	5.6 de	3.8 f	3.9 g	0.65 cde	0.86 de
	20	4.8 f	3.4 g	3.5 h	0.73 bc	0.75 e
			Trial 3			
Control[y]		6.2 a	6.4 b	*[v]	1.59 a	*
BC_{20}	40	5.5 bc	7.2 a	*	0.87 b	*
	30	5.8 b	5.9 c	*	0.82 bc	*
	20	5.2 cd	4.7 e	*	0.81 bc	*
BC_{10}	40	5.1 cd	6.3 b	*	0.75 cd	*
	30	5.3 cd	5.0 d	*	0.75 cd	*
	20	5.4 bcd	4.5 f	*	0.77 bcd	*
BC_6	40	4.3 e	4.6 f	*	0.69 d	*
	30	3.8 f	4.2 g	*	0.70 cd	*
	20	4.1 ef	3.8 h	*	0.79 bcd	*

[z] Hardwood biochar sizes include BC_6 (diameter between 3.36 mm and 1.19 mm), BC_{10} (diameter between 2.38 mm and 0.595 mm), and BC_{20} (diameter between 0.841 mm and 0.420 mm).

[y] Control substrate was the standard commercial soilless substrate Sunshine LC1 (Sun Gro Horticulture, Agawam, MA).

[x] Substrate composition indicates percentage of biochar with balance sphagnum peat. Biochar and sphagnum peat substrates had no limestone added, whereas the control substrate was amended with limestone during formulation.

[w] Means within a column followed by the same lowercase letter are not different according to Fisher's least significant difference test ($P \leq 0.05$, n = 5).

[v] A * indicates data were not collected.

CHAPTER 4. SUMMARY AND CONCLUSION

Summary

Biochar can replace perlite in greenhouse soilless substrates. Without limestone amendment, biochar blended with sphagnum peat provided pH values that allowed for normal plant growth. Using biochar as a replacement for perlite eliminates the need for amendment with limestone. Substrates containing biochar can grow most plants as well as or better than the control substrate used in these experiments. Even with lower initial EC values, biochar-containing substrates produced plants with equal or greater shoot dry mass compared to plants grown in the control substrate. All but one substrate tested provided physical properties recommended for use in containers (Arnold Bik, 1983; Boertje, 1984; Bunt, 1988). One biochar-containing substrate, 30% BC_{10}, matched the pH and physical properties of the commercial substrate, with the exception of bulk density.

Substrate pH increased as the amount of biochar increased. Due to the base-rendering nature of this type of biochar, and reports of biochar raising pH levels in field studies (Laird, 2008), increased pH was expected as the amount of biochar in the substrate increased. Several biochar-containing substrates had pH values similar to the commercial substrate over time (Fig. 2.3). This shows the capacity of biochar to serve as a liming agent, in addition to its effects on the physical properties. The limestone normally added to soilless substrates can be eliminated when biochar is substituted for perlite. The elimination of limestone amendment alone greatly simplifies the formulation of substrates containing relatively large volumes of sphagnum peat. In addition, biochar could facilitate the adjustment of substrate pH by increasing or decreasing the amount or the size of biochar in the substrate.

Growth in biochar-containing substrates varied among the crops tested. In several instances, such as tomato in trials 2 and 3, growth was greatest in the control substrate. The biochar size and ratio that led to the greatest dry mass varied among crops. This was expected, as there is no single soilless substrate that is optimal for all crops in all situations. Additionally, field investigations indicate the amount of biochar to add for optimum plant growth varies and may have to be determined for each plant (Glaser et al., 2002).

Electrical conductivity (EC) of a substrate extract is an indication of fertilizer concentration (Nelson, 2012). The initial EC measurement of each substrate was taken at 14 days after transplanting, and it was greater in the control (Tables 3.1 to 3.7). This was due to the starter fertilizer charge contained in the control substrate. In many cases, the initial EC of the control substrate was twice that of the biochar substrates, which contained no starter fertilizer charge. Despite this advantage, dry mass was often equal to or greater in plants grown in substrates containing biochar. We hypothesize this effect is due to the combination of the ability of biochar to hold and slowly release nutrients in a soilless substrate (Altland and Locke, 2012) and the potential for biochar itself acting as a fertilizer (Glaser et al., 2002).

There are no standards for physical properties of greenhouse substrates, but several recommendations have been proposed. Minima of 85% total pore space and 45% water-filled pore space have been recommended (Arnold Bik, 1983; Boertje, 1984). All biochar-containing substrates in this study met these minima, except for 40% BC_6, which had 82.4% total porosity. All substrates tested also met the recommendation of Bunt (1988) of at least 10% to 20% air-filled pore space (Table 2.1). Bulk densities of all substrates tested were greater than the commercial substrate. Two substrates, 30% BC_{10} and 40% BC_{20}, were the same as the commercial substrate in total porosity, air space, and container capacity (Table 2.1). In addition, the pH of 30% BC_{10} also was the same as that of the control during the first nine weeks of the study, whereas the pH of 40% BC_{20} was greater.

Conclusion

Based on pH values, physical properties, and plant growth in each substrate, a ratio of 30% BC_{10} to 70% sphagnum peat seems to be optimum. This substrate was the same as the commercial control in all measures except bulk density, which was greater for 30% BC_{10} (Table 2.1). Bulk density is of particular interest when plants or substrate are shipped, as increased bulk density translates into (slightly) increased freight costs.

If biofuel production via biomass pyrolysis continues to increase, availability of biochar will increase, likely leading to a decrease in the relative cost of biochar. This, along with the benefits and value-added potential of biochar, may work to defray any additional shipping costs associated with increased bulk density. Biochar is a stable form of carbon, and additions of biochar to soil are considered a means of carbon sequestration (Laird, 2008). Marketing plants grown in biochar-containing substrates as a green product that sequesters carbon may allow for larger margins and greater profits for industry.

Despite the increased bulk density, these results illustrate the potential for biochar to replace perlite in commercial, general-use soilless substrates. Other alternate components, such as Growstones and parboiled fresh rice hulls, have been found suitable as perlite replacements (Evans, 2011). These components can provide the physical properties needed for plant growth, but they do not eliminate the need for amendment with limestone. Additionally, using biochar in substrates potentially adds value to biochar, while creating an opportunity for carbon sequestration (Dumroese et al., 2011). Reports of biochar amendments to soilless substrates resulting in improved plant growth (Graber et al., 2010), biochar-induced systemic resistance to disease (Elad et al., 2010), and increased nutrient retention (Altland and Locke, 2012), combined with these results, make biochar an especially attractive component for soilless greenhouse substrates.

Future Research

Biochar is a blanket term for the solid charcoal product produced during pyrolysis. Because the properties of biochar depend on pyrolysis conditions and the original biomass, there is considerable diversity among materials known as biochar. This research was conducted using hardwood biochar produced by slow pyrolysis and the results are specific to this material. Although similarly produced biochar products are widely available from commercial sources, the general designation of ‘slow pyrolysis hardwood biochar’ does not guarantee similar properties, and therefore, results may differ. Basic characterization of the properties of the biochar used in this study is necessary to identify biochar materials that could be expected to produce similar results. Most important is identification of the ash content, which affects the calcium carbonate equivalent of the biochar and directly impacts the pH of the prepared substrate. Proximate analysis of the biochar used here would provide this information; however, these tests were beyond the scope and timeframe of this project.

Results from these experiments demonstrate this type of hardwood biochar eliminates the need for limestone amendment and plants can grow normally in these substrates. In some cases, plants seemed to be healthy and growing normally at a pH typically considered detrimental to the health of the plant. An example of this is trial 2 petunia grown in 40% BC_{20}, which had a mean pH of 7.6 (Table 3.3). According to Cavins et al. (2000), the target pH range for petunia is 5.4 to 5.8, with management decisions suggested before the pH exceeds 6.0. Our petunias grew at a much greater pH, and they did not show noticeable indications of an elevated pH. It is important to note this was an observation, and no nutrient testing was conducted during these experiments. The potential to achieve normal plant growth at an elevated pH when grown in biochar-containing substrates is an exciting possibility. Additional benefits may exist if biochar is found to increase the pH range in which high-quality plants can be grown. However, this aspect of using biochar in substrates requires additional evaluation.

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