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Determining Eastern Red Cedar Biochar Soilless Media Supplementation Rates for Potted Ornamental Kale and Chrysanthemum Production

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Abstract. **The increasing demand for soilless media, sustainability issues with peatmoss, and increasing cost of peatmoss have prompted studies of more environmentally friendly and less expensive substitutes. Biochar, a lightweight black carbon material produced by the pyrolysis of biomass, has gained popularity as a soilless media supplement. The objective of this study was to evaluate Eastern red cedar (ERC) biochar as a supplement to soilless media for the production of chrysanthemum and ornamental kale. Treatments included ERC biochar produced at three different temperature ranges of 300 to 350 °C, 400 to 450 °C, and 500 to 550 °C that were applied at 25%, 50%, and 75% v/v plus a control (100% v/v of standard commercial mix). Additionally, ERC bark was applied at the same rate as biochar. The 300 to 350 °C and 400 to 450 °C temperature ranges increased the bulk density of the media, whereas total porosity was greatest with just bark. Regarding the physical properties of the media, in general, the 75% v/v supplementation rate of ERC bark or biochar at any temperature increased air porosity but decreased the water holding capacity, except for the water holding capacity at 500 to 550 °C. As the biochar production temperature increased, so did the pH and electrical conductivity (EC), whereas volatile matter decreased. Plant height, width, shoot dry weight, root dry weight, number of flowers (chrysanthemum only), flower diameter, and water use efficiency were greatest with the 100% v/v soilless media for both species. In general, chrysanthemum plants grown with 25% v/v biochar supplementation or bark had similar height, width, and shoot dry weight at any temperature compared with those grown with the 100% v/v soilless media. For ornamental kale, the 25% v/v 400 to 450 °C biochar supplementation showed plant height and water use efficiency similar to those of the 100% v/v soilless media. In general, 25% ERC bark performed similar to 25% v/v and 50% v/v biochar at any temperature for plant width, shoot dry weight, root dry weight, water use efficiency, and root-to-shoot ratio. The media nutrient content and EC were greater with 100% v/v soilless media and a lower rate (25% v/v) of ERC bark and biochar than with higher rates. The higher levels of biochar were harmful and reduced the ornamental kale growth and quality. These results suggest that supplemented soilless media with lower rates (25% v/v) of ERC biochar could be recommended for chrysanthemum, but that less than 25% v/v may be necessary for ornamental kale.**

In the greenhouse and nursery industry, soilless media serve as the basis for potted plant production and contain inorganic and organic elements (Bilderback et al. 2005). Peat moss is often used in the growing media because of its beneficial features, such as the water holding capacity (WHC) and high air capacity at 100% WHC, lack of weeds and pathogens, low bulk density, and nutrient retention (Fryda et al. 2018; Schmilewski 2008). However, studies of peat substitutes in soilless media have been prompted by factors such as the increasing cost of peat, the impact of its harvest on wetland ecosystems, the loss of peat lands as a significant global carbon (C) sink, and the perceived unsustainability of peat (Karki 2018; Margenot et al. 2018). Additionally, the harvesting and extraction of peatland elevate the aerobic condition, releasing the CO_2 previously stored in peatland as a result of anaerobic conditions and slow peat decomposition (Waddington and McNeil 2002; Waddington and Price 2013). As a replacement for peatmoss, biochar has gained popularity.

Biochar is the C-rich organic matter that remains after pyrolysis (heating in the absence of oxygen) of biomass (Altland and Locke 2012) that converts organic matter to a vapor phase and solid biochar residue (Northup 2013). Biochar is gaining attention because of its properties such as greater air porosity, low density, high nutrient and water retention capacities, higher cation exchange capacity, and increased pH (Margenot et al. 2018; Nair and Carpenter 2016). Prasad et al. (2018) found that biochar application (along with peat) at greater rates resulted in significant reductions of electrical conductivity (EC) and NO_3^- (up to 95%) levels but increased potassium (K) levels. Similar results were found by Chrysargyris et al. (2020), who reported decreased EC with increased rates of biochar (7.5%–15%). In contrast to the bulk density, which was greatest at the biochar concentration of 100%, the nitrogen (N) and phosphorus (P) contents were greatest with growing media with a biochar concentration of 0% (Sabatino et al. 2020). In addition to the nutrient supply, biochar improved the retention of nutrients and water in the growing media by enhancing the cation exchange capacity and proportion of pore space (Kim et al. 2017). Nutrient availability also increases because of the ability of biochar to reduce nutrient leaching (Yamato et al. 2006). Studies have found that the concentration of negative charges on biochar interfaces (Cheng et al. 2006) and the adsorption of charged organic compounds increase with the aging of biochar (Liang et al. 2006).

Both research and review articles have confirmed a growing interest in the use of biochar as a peat replacement (Huang and Gu 2019). In addition to peat substitution, the horticultural interest in biochar is related to its use for plant protection through improvements in microbial activities and increasing water storage (Blok et al. 2017; Graber et al. 2010). However, knowledge of the rate at which biochar can be a substitute for peatmoss as an amendment is important (Margenot et al. 2018). Biochar use is affected by many factors, including the type of feedstock, production methods, and production temperatures, soils, climates, and crop conditions (Gelardi et al. 2021; Regmi et al. 2022). Therefore, the biochar properties may vary with the change in the biomass source and production process. Because of the multifactorial influence on biochar properties, the same biochar feedstock may have diverse effects on different plant species, whereas biochar from different sources may affect the same plant differently.

A previous study reported that similar to 100% peatmoss, 25% conifer wood biochar (produced at 450 °C) supplementation resulted in the greatest plant height and number of flowers for rose (*Rosa rugosa* T.) plants (Fascella et al. 2018). Additionally, viola (*Viola cornuta* L.) grown in hardwood biochar mixtures of 10% and 25% (w/w) improved plant biomass, root length, and flowering; however, 50% biochar reduced plant growth and flowering (Regmi et al. 2022), suggesting that an increased biochar application rate negatively impacted plant growth. Higher rates of biochar have a negative impact on plant growth because of the high pH (Margenot et al. 2018). Because biochar is a C-rich matter, a higher biochar rate might exhibit a high C:N ratio, high pH:EC ratio, and greater N binding within itself, thus hindering its release to plants and influencing the plant growth (Atkinson et al. 2010; Zulfiqar et al. 2021).

The selection of appropriate feedstock is important because the physical and chemical properties of the biochar depend on the type of feedstock. Roberts et al. (2010) mentioned that the feedstock collection and pyrolysis process are major contributes to the primary cost of biochar production. Additionally, the use of less expensive and easily available feedstock would be economically viable. Feedstock that is easily and locally available is inexpensive and sometimes free, thus making it less expensive to produce biochar. Recently, Eastern red cedar (*Juniperus virginiana* L.) (ERC) has been a problem for farmers because it affects the availability of water and space for crops and wildlife species (Zhang and Hiziroglu 2010). The uncontrolled expansion of ERC had started to affect the composition of diverse plant and animal communities by displacing the native plants, thus leading to the development of monoculture (Dunford et al. 2007; Smith 2011). However, a recent study by Vaughn et al. (2021) showed that ERC biochar possesses desirable properties like high porosity, EC, and pH, which make it a suitable supplement for soilless media. Additionally, the pyrolysis temperature used for biochar preparation is an important factor in determining the physical and chemical properties of biochar. However, there have been few reports of ERC biochar prepared at different temperatures and tested for the production of ornamental plants.

Chrysanthemum (*Chrysanthemum* L.) is an ornamental plant produced as both a cut plant and potted plant (Van Der Ploeg and Heuvelink 2006). Chrysanthemum showed the greatest growth index and shoot fresh weight at 60% biochar:40% peatmoss (Peng et al. 2018). Similarly, rice (*Oryza sativa* L.) straw biochar at 10% showed the greatest number of flowers and dry weight of 'Hangbaiju' chrysanthemum, which decreased when the biochar rate increased to 20%. In the same study, the flavonoids yield and concentration were greatest with 20% biochar produced at 500 °C (Chen et al. 2018). Ornamental kale (*Brassica oleracea* L. var. *acephala*) is an ornamental plant known for its colorful (green, purple), cracked, waved leaves and cold resistance (Liu et al. 2017). According to Kim et al. (2017), 5% rice hull biochar at 500 °C increased ornamental kale shoot and root dry weights and N, P, and K contents in the shoot, which were attributed to increased available water and N retention. This showed that biochar has diverse effects on the plant performance and nutrient content of plants and growing media.

Therefore, this study was conducted to evaluate the use of biochar produced by the pyrolysis process for ERC bark under different temperatures at different rates in soilless media for the greenhouse production of ornamental plants. This study aimed to determine the suitability of ERC biochar as an alternative for soilless media because limited studies of its effect on potted plants and the encroaching expansion of ERC in the United States have been performed. We hypothesized that the lower rate of biochar will outperform the higher rate of biochar.

Materials and Methods

Preparation of biochar. Biochar was prepared from ERC bark (Custom Wood Fibers & Cedar Mulch, LLC, Stillwater, OK, USA) through the pyrolysis process using a double-barrel system (Lamichhane et al. 2023). Seasoned wood (35 cm × 15 cm) from Payne Country Tree Service (Stillwater, OK, USA) was placed between the small and large barrels to create a fire. Biochar was produced by pyrolysis of the ERC biomass at three temperature ranges of 300 to 350 °C, 400 to 450 °C, and 500 to 550 °C for 3 h after the temperature reached the set point.

Plant materials and growth conditions. The experiment was conducted at the Department of Horticulture and Landscape Architecture Research Greenhouses of Oklahoma State University located in Stillwater, OK, USA. The greenhouse temperature was set at 25.8 ± 1.6 °C (hourly averaged data). No additional light was used, and the daily light integral averaged 14.5 ± 0.5 $mol·m^{-2}·d^{-1}$. 'Fringed Nagoya Red' ornamental kale (*Brassica oleracea* L.) was obtained from Park Seed (Greenwood, SC, USA) in a 288-cell tray. Ornamental kale was transplanted as one plug per standard azalea (diameter, 15.24 cm) pot. Rooted cuttings of 'Aduro Orange' chrysanthemum (*Chrysanthemum* L.) plants from Ball Horticulture (West Chicago, IL, USA) were planted on 4 Aug 2022, and four chrysanthemum rooted cuttings were transplanted and equally spaced in each pot. Chrysanthemum cuttings were pinched at seven nodes 2 weeks after transplanting. Pinching was performed to induce the lateral branches, thus increasing the number of flowers. Plants were irrigated through pressure-compensated drip emitters at a rate of 7.5 L/hr and fertilized with 200 $mg·L^{-1}$ N and 20N–4.3P–16.6K fertilizer (J.R Peter's Inc., Allentown, PA, USA).

Treatment and experimental design. Biochar produced at each temperature was mixed with soilless media (Berger 45% v/v bark; Berger, Saint Modeste, Quebec, Canada) at ratios by volume of 75%:25%, 50%:50%, and 25%:75% biochar:soilless media; a control with only soilless media was also used. Additionally, ERC bark not converted to biochar at 75:25, 50:50, and 25:75 ERC bark:-soilless media was included. The experiment was conducted as a split-plot design with 13 treatments with the media ratio as the main plot, and biochar temperature and ERC bark were randomized as the subplot. Based on the volume of the potting mixture, four tables were randomly assigned; then, ERC bark and temperature factors were randomized within each table. The particle size of biochar used for this research ranged from 2 mm to 20 mm. The replication consisted of eight pots per treatment, and the experiment was repeated. There were 104 pots per replication and a total of 208 pots per species.

Data Collection

Physical properties of growth media. Regarding media physical properties, biochar and ERC bark were mixed with soilless media as mentioned for the treatment described. The samples were prepared separately to determine the physical properties distinct from the pots used for planting the ornamentals. Bulk density (media weight/media volume), percent porosity (mL of water to media/total mL of media), percent air space [volume of drained water (mL)/total mL of media), and WHC (percent porosity − percent air space) were based on the work of Davidson et al. (2000) using an in situ technique comprising plastic bags punctured with five equally spaced 0.3-mm holes in the bottom (five holes per bag).

Properties of ERC bark and biochar. Five samples per temperature treatment were used for the analysis. These samples were not the same samples used for physical properties. The moisture content, ash content, volatile matter content (vapor or gases released during heating of biomass) (Basu 2010), and fixed C were determined using the ASTM D1762-84 protocol (2007), which is a standard test method for the proximate analysis of biochar at the Bioenergy Laboratory (Stillwater, OK, USA). The pH, EC, total C, and cation exchange capacity were determined according to the methodology proposed by Gavlak et al. (2003) and Page (1983).

Plant growth parameters. Soil moisture from five pots per treatment was measured daily using an analog meter (XLUX, Shiyan, China) inserted to a depth of 5 cm during the morning. After inserting the meter, it was left undisturbed for 30 s to stabilize the reading. The meter had the following possible readings: 1 to 3, dry; 4 to 7, moist; and 8 to 10, wet. After averaging overall treatments, an analog reading of ≤3 was used as the basis

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Table 1. Bulk density (BD), total porosity (TP), aeration porosity (AP), and water holding capacity (WHC) of 13 different potting mixes determined using a 15.24-cm pot.

Temperature range (°C)	Media ratio[i] (v/v)	BD ($kg \cdot m^{-3}$)	TP (% v/v)	AP (% v/v)	WHC (% v/v)
Soilless media	100 soilless media	220.5 d[ii]	68.0 d	20.0 g	48.1 a
ERC bark	25 ERC bark:75 soilless media	219.3 d	84.8 a	37.7 b	47.2 ab
ERC bark	50 ERC bark:50 soilless media	228.0 cd	84.7 a	39.5 b	45.1 ab
ERC bark	75 ERC bark:25 soilless media	192.2 e	79.8 ab	47.5 a	32.3 d
300–350	25 biochar:75 soilless media	246.0 ab	68.5 cd	22.5 gf	46.0 ab
300–350	50 biochar:50 soilless media	264.0 a	70.2 cd	24.2 ef	45.9 ab
300–350	75 biochar:25 soilless media	251.3 a	63.4 d	29.4 cd	34.0 d
400–450	25 biochar:75 soilless media	255.3 a	70.7 bcd	23.0 efg	47.7 ab
400–450	50 biochar:50 soilless media	249.0 ab	65.3 d	24.3 ef	41.1 b
400–450	75 biochar:25 soilless media	255.3 a	62.4 d	27.2 de	35.2 cd
500–550	25 biochar:75 soilless media	244.9 bc	64.1 d	22.5 gf	41.6 b
500–550	50 biochar:50 soilless media	238.7 c	66.0 d	26.0 def	40.0 bc
500–550	75 biochar:25 soilless media	236.9 c	74.3 bc	33.0 c	41.3 b
Significance		<0.001	<0.001	<0.001	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 5) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

for irrigation. At the time of harvest (12 weeks after transplanting for chrysanthemum and 10 weeks after transplanting for ornamental kale), measurements of plant height (from the top of the pot to the top of the plant), plant width (two perpendicular), days to flowering, numbers of flowers, flower diameter (for chrysanthemum), and root-to-shoot ratio were obtained. These measurements were obtained for all plants in the experiment. Two leaves from the middle part of each plant were selected to measure plant greenness in the middle part of the leaves using a chlorophyll meter (atLEAF; FT Green LLC, Wilmington, MA, USA). The roots were washed, cleaned, and oven-dried at 60 °C for 3 d to determine the dry weight. The total amount of water applied to each plant was recorded to determine the water use efficiency (WUE) (shoot and root dry weight/total amount of water applied). The total water measurement was taken for all plants in the experiment. Two samples of both species (two leaves from all the plants of the treatment for ornamental kale and single plant as a sample for chrysanthemum) and soil from each treatment per replication were chosen for the total nutrient analysis and submitted to the Soil, Water, and Forage Analytical Laboratory at Oklahoma State University, which uses a LECO TruSpec Carbon and Nitrogen Analyzer (LECO Corporation, St. Joseph, MI, USA) for analysis (Zhang and Henderson 2016).

Statistical analysis. Statistical analysis was performed using PROC GLIMMIX in SAS/STAT software (version 9.4; SAS Institute, Cary, NC, USA). Tests of significance were reported at the 0.05, 0.01, and 0.001 levels. When F-values were significant, Tukey's highly significant difference multiple comparison methods were used to separate the means. Significant differences between means were estimated at 95% confidence levels.

Results

Physical properties of growth media. Bulk density, total porosity, aeration porosity, and water-holding capacity of the potting mixes had significant treatment effects (Table 1). The greatest bulk density was recorded at 50% biochar at 300 to 350 °C which was similar to 25% v/v and 75% v/v biochar of 300 to 350 °C, 25% v/v, 50% v/v, and 75% v/v biochar of 400 to 450 °C. The 25% v/v ERC bark increased the total porosity by 24.70% compared with 100% v/v soilless media. Similarly, the greatest aeration porosity was observed with 75% v/v ERC bark, which was 137.5% greater compared with the 100% v/v soilless media. However, the greatest water holding capacity was observed with the 100% v/v soilless media and was similar to that observed with 25% v/v ERC bark and 50% v/v ERC bark, 25% v/v biochar and 50% v/v biochar at 300 to 350 °C, and 25% v/v biochar at 400 to 450 °C. The addition of biochar and bark reduced the water-holding capacity of the media by 13.51% to 32.85% compared with 100% v/v soilless media.

Properties of ERC bark and biochar. There was a significant treatment effect for all the properties of ERC bark and biochar (Table 2). Pyrolysis at 300 to 350 °C, 400 to 450 °C, and 500 to 550 °C led to decreases in volatile matter by 39.95%, 67.75%, and 56.19% compared with ERC bark, respectively. Biochar produced at 300 to 350 °C had the highest moisture content, which was similar to that observed with biochar at 500 to 550 °C. Biochar at 400 to 450 °C had the greatest fixed C, which was different from that observed with other treatments. The ash content of biochar at 400 to 450 °C was six-times greater than that observed with ERC bark and was similar to that observed with biochar at 500 to 550 °C. The biochar at 500 to 550 °C showed the greatest pH value, which was increased by 67.27% compared with that observed with ERC bark. Biochar produced at 500 to 550 °C had the greatest EC, which was similar to that observed with ERC bark. The greatest cation exchange capacity and total C were observed with biochar at 400 to 450 °C.

Table 2. Properties of Eastern red cedar (ERC) bark and biochar produced at different temperature.

Temperature (°C)	Volatile matter (% w/w)	Moisture (% w/w)	Ash content (% w/w)	Fixed carbon (% w/w)	Total carbon (% w/w)	pH	EC ($\mu S \cdot cm^{-1}$)	CEC ($cmol \cdot kg^{-1}$)
ERC bark	83.1 a[i]	11.6 b	1.0 c	4.3 d	47.1 d	5.5 d	216.7 ab	8.2 c
300–350	49.9 b	21.9 a	2.8 bc	25.5 c	57.9 c	8.4 c	104.1 c	3.8 d
400–450	26.8 d	7.2 b	6.0 a	60.0 a	71.9 a	8.9 b	177.7 b	19.3 a
500–550	36.4 c	21.1 a	4.1 ab	38.4 b	63.3 b	9.2 a	273.9 a	11.4 b
Significance	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[i] Means (n = 5) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

Volatile matter + moisture + ash content + fixed carbon = 100.

CEC = cation exchange capacity; EC = electrical conductivity.

Table 3. Effects of 13 different potting mix ratios on growth and plant quality of chrysanthemum 'Aduro Orange' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	Ht (cm)	Width (cm)	Shoot dry wt (g)	Root dry wt (g)	No. of flowers	Flower diam (cm)	WUE ($mg \cdot mL^{-1}$)	Root-to-shoot ratio
Soilless media	100 soilless media	18.7 a[ii]	41.7 a	37.2 a	3.8 a	392 a	5.0 a	2.7 a	0.1 ab
ERC bark	25 ERC bark:75 soilless media	17.7 abc	38.7 bc	29.2 b	2.6 b-e	224 ab	4.9 ab	2.2 b	0.07 bc
ERC bark	50 ERC bark:50 soilless media	15.6 e	33.3 f	18.3 e	1.7 f	145 b	4.4 bc	1.6 c	0.08 abc
ERC bark	75 ERC bark:25 soilless media	12.2 f	24.2 g	6.6 f	0.5 g	62 b	4.0 c	0.7 d	0.05 c
300–350	25 biochar:75 soilless media	18.0 ab	39.9 ab	29.7 b	2.7 b-e	208 ab	4.9 a	2.3 ab	0.08 abc
300–350	50 biochar:50 soilless media	16.4 cde	35.8 def	23.6 cd	2.4 b-f	173 b	4.7 ab	2.1 b	0.09 abc
300–350	75 biochar:25 soilless media	16.2 cde	34.2 ef	18.3 e	2.1 ef	219 ab	4.7 ab	1.6 c	0.1 ab
400–450	25 biochar:75 soilless media	18.3 ab	39.8 ab	30.7 b	2.9 bc	220 ab	5.0 a	2.4 ab	0.08 abc
400–450	50 biochar:50 soilless media	17.2 bcd	37.4 bcd	25.5 c	2.3 cdef	180 b	4.8 ab	2.2 b	0.07 bc
400–450	75 biochar:25 soilless media	16.8 bcde	34.4 ef	19.5 e	2.1 edf	133 b	4.9 ab	2.1 b	0.1 ab
500–550	25 biochar:75 soilless media	17.9 ab	39.4 abc	31.5 b	2.9 bcd	219 ab	4.9 a	2.4 ab	0.07 bc
500–550	50 biochar:50 soilless media	17.5 abc	36.9 cde	25.3 c	3.1 ab	182 b	4.8 ab	2.3 ab	0.1 a
500–550	75 biochar:25 soilless media	16.0 ed	35.0 def	20.3 de	2.3 c-f	139 b	4.9 ab	2.1 b	0.09 abc
Significance		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system; Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 16) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

WUE = water use efficiency.

Chrysanthemum growth and development. In chrysanthemum, there was a significant effect of different potting mixes for all growth parameters except for plant greenness, which ranged from 53.4 to 55.4, and days to flowering, which ranged from 75.3 to 76.4 d (Table 3). As the biochar rate increased from 25% v/v to 75% v/v, the plant height, plant weight, shoot and root dry weight, number of flowers, flower diameter, and WUE decreased. The greatest plant height was observed with 100% v/v soilless media; however, it was not different from that observed with 25% v/v biochar at all three temperatures. Similarly, the greatest width was observed with 100% v/v soilless media; however, it was not different from that observed with 25% biochar at 300 to 350 °C and 500 to 550 °C. The 50% v/v biochar reduced the plant height and width up to 14.44% and 17.99%, respectively. Additionally, ERC bark showed the greatest reduction in plant growth compared with that observed with 100% v/v soilless media. The shoot dry weight with 100% v/v soilless media was greatest by 24% to 86%, depending on the treatment. The greatest root dry weight was observed with the 100% v/v soilless media, and it was significantly similar to that observed with 50% v/v biochar at 500 to 550 °C. The greatest number of flowers was observed with 100% v/v soilless media. Biochar and ERC bark application reduced the flower numbers by 66.07% and 84.18% respectively. The flower diameter was greatest with 100% v/v soilless media and 25% v/v biochar at 400 to 450 °C, and it was only different from the diameters observed with 50% v/v and 75% v/v ERC bark. The ERC bark and biochar with greater than 25% v/v reduced the WUE of growing media compared with the WUE observed with 100% v/v soilless media. The greatest root-to-shoot ratio was observed with 50% v/v biochar at 500 to 550 °C, and it was only different from that observed with 25% v/v and 75% v/v ERC bark, 50% v/v biochar at 400 to 450 °C, and 25% v/v biochar at 500 to 550 °C.

Chrysanthemum leaf nutrients. The effect of potting mixes was significant for different leaf nutrients of chrysanthemum except for Fe as all values ranged from 105.0 to 139.1 $mg \cdot L^{-1}$ (Table 4). The greatest total nitrogen (TN) content was recorded with 100% v/v soilless media, which was only different from that observed with 50% v/v ERC bark, 50% v/v biochar at all three temperatures, and 75% v/v biochar at 500 to 550 °C. The greatest P was recorded with 100% v/v soilless media and 25% v/v ERC bark. The 75% v/v biochar at 500 to 550 °C showed the greatest calcium (Ca) content, which was 17.65% greater than that with 100% v/v soilless media. The 75% v/v ERC bark showed the greatest K content in leaves. Similarly, the greatest magnesium (Mg) content was recorded with 100% v/v soilless media and 25% v/v ERC bark. The 500 to 550 °C biochar reduced the Mg content by 50% compared with the 100% v/v soilless media. The greatest sulfur (S) content was observed with the 75% v/v ERC bark treatment, but it was only different from the content with the 25% v/v and 50% v/v biochar at 500 to 550 °C, 50% v/v biochar at 400 to 450 °C, 25% v/v biochar at 300 to 350 °C, and 50% v/v ERC bark. Regarding the copper (Cu) content, that with the 75% v/v ERC bark was the greatest and similar to that with 100% soilless media. The ERC bark greater than 25% v/v resulted in a reduction of the boron (B) content in the leaf, but the other treatments showed similar effects with up to 100% soilless media. The zinc content was the greatest with the 25% v/v ERC bark, which was similar to that with the 100% v/v soilless media, whereas 75% v/v ERC bark increased the manganese (Mn) content by three-times compared with that observed with the 100% v/v soilless media.

Chrysanthemum media nutrients. Different types of potting mixes had significant effects on the soil nutrient content of chrysanthemum (Tables 5 and 6). Ammonium was greatest with 25% v/v ERC bark, which was similar to that observed with 50% v/v ERC bark and 75% v/v ERC bark, 100% v/v soilless media, and 25% v/v biochar at 300 to 350 °C and 500 to 550 °C. The nitrate content decreased with greater biochar rates. However, the addition of ERC bark and biochar both reduce the P content of media. Additionally, the greater rates of biochar and ERC bark increased the K content; however, the opposite trend was observed for the Ca content. The Mg content was greatest with 100% v/v soilless media; this content was similar to that observed with all other treatments except 75% v/v ERC bark, 50% v/v biochar, and 75% v/v biochar at 500 to 550 °C.

Table 4. Effect of 13 different potting mix ratios on the leaf nutrients of chrysanthemum 'Aduro Orange' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	TN (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	B (mg·L^{-1})	Zn (mg·L^{-1})	Cu (mg·L^{-1})	Mn (mg·L^{-1})
Soilless media	100 soilless media	4.8 a[ii]	0.8 a	4.6 a-d	1.7 bcd	0.2 a	0.4 ab	88.3 a	110.1 ab	6.0 ab	187.4 fg
ERC bark	25 ERC bark:75 soilless media	4.7 ab	0.8 a	4.7 abc	1.8 abcd	0.2 a	0.4 ab	81.6 a	116.7 a	5.4 abc	208.1 efg
ERC bark	50 ERC bark:50 soilless media	4.0 d	0.5 bcde	3.7 cd	1.6 d	0.1 b	0.3 b	64.2 bc	65.5 c	3.5 c	259.8 defg
ERC bark	75 ERC bark:25 soilless media	4.3 abcd	0.6 b	5.3 a	2.0 abc	0.2 ab	0.4 a	63.3 c	96.2 abc	7.0 a	563.3 a
300–350	25 biochar:75 soilless media	4.4 abcd	0.5 bcd	4.2 bcd	1.7 bcd	0.2 ab	0.3 b	74.3 abc	85.8 abc	4.0 c	152.3 g
300–350	50 biochar:50 soilless media	4.1 bcd	0.4 cde	3.8 cd	2.0 ab	0.2 ab	0.4 ab	81.8 a	79.2 abc	3.8 c	410.6 bc
300–350	75 biochar:25 soilless media	4.3 abcd	0.4 e	4.3 bcd	2.0 ab	0.1 b	0.4 ab	73.8 abc	67.4 bc	4.4 bc	330.4 cd
400–450	25 biochar:75 soilless media	4.5 abc	0.6 b	4.6 abcd	2.0 abc	0.2 ab	0.4 ab	84.8 a	88.6 abc	4.8 bc	307.6 cde
400–450	50 biochar:50 soilless media	4.2 bcd	0.4 e	3.9 bcd	1.6 cd	0.2 ab	0.3 b	75.2 abc	78.1 abc	3.6 c	337.5 cd
400–450	75 biochar:25 soilless media	4.3 abcd	0.4 e	4.9 ab	1.9 abc	0.1 b	0.4 ab	87.2 a	64.1 c	4.0 bc	514.6 ab
500–550	25 biochar:75 soilless media	4.6 ab	0.6 bc	4.4 a-d	1.7 bcd	0.1 b	0.4 b	79.3 ab	66.5 c	3.9 c	167.5 fg
500–550	50 biochar:50 soilless media	4.0 cd	0.4 de	3.6 d	1.7 abcd	0.1 b	0.3 b	78.2 abc	65.6 c	3.8 c	277.3 def
500–550	75 biochar:25 soilless media	4.2 bcd	0.4 de	4.4 abcd	2.0 a	0.1 b	0.4 ab	87.6 a	64.1 c	4.0 c	376.7 cd
Significance		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 4) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

B = boron; Ca = calcium; Cu = copper; K = potassium; Mg = magnesium; Mn = manganese; P = phosphorus; S = sulfur; TN = total nitrogen; Zn = zinc.

The 75% v/v biochar application increased the pH of media by 22.38% compared with that observed with the 100% v/v soilless media application (Tables 5 and 6). However, an increase in the biochar rate significantly decreased the B content in media, with the lowest value recorded with 50% v/v biochar and 75% v/v biochar at 500 to 550 °C. Additionally, the lowest EC and sodium (Na) were recorded with the 75% ERC bark application. The greatest chloride content was observed with 25% v/v biochar at 400 to 450 °C, and it was only different from that with 50% v/v biochar at 500 to 550 °C. Similarly, the greatest S content was recorded with 25% v/v biochar at 400 to 450 °C, and it was similar to that with all other treatments except 75% v/v ERC bark.

Ornamental kale growth and development. Regarding ornamental kale, there was a significant potting mix effect for all growth parameters except plant greenness because all values ranged from 52.0 to 57.5 (Table 7). An increase in the biochar application reduced the plant height, with the greatest height observed with 100% v/v soilless media; this height was similar to that observed with 25% v/v biochar at 400 to 450 °C. Similarly, plant width, shoot dry weight, and root dry weight were greatest with 100% soilless media and reduced with the application of biochar. The greatest WUE was observed with less than 100% v/v soilless media, and it was decreased up to 75% with ERC bark and up to 35% with biochar. The greatest root-to-shoot ratio was observed with 75% v/v biochar at 500 to 550 °C, and it was only different from that observed with 25% v/v and 50% v/v biochar at 300 to 350 °C and at 400 to 450 °C and with 50% v/v biochar at 500 to 550 °C.

Ornamental kale leaf nutrients. Different potting mix treatments had significant effects on TN, Mg, and Mn; however, no differences in P (range, 0.4%–0.6%), K (range, 3.4%–4.0%), S (range, 0.6%–0.7%), B (range, 42.6–53.5 mg·L^{-1}), Fe (range, 103.2–330.2 mg·L^{-1}), Zn (range, 44.5–118.9 mg·L^{-1}), and Cu (range, 1.5–1.8 mg·L^{-1}) were observed (Table 8). Higher temperatures and higher rates (75% v/v) of biochar reduced the TN content by 20% compared with that observed with 100% v/v soilless media. The greatest Mg content was observed with 100% v/v soilless media, and it was only different from that observed with 75% ERC bark. Along with increasing rates of ERC bark and biochar from 25% v/v to 75% v/v, the Mn content increased and was greatest with 50% v/v biochar at 400 to 450 °C.

Ornamental kale soil nutrients. Different potting mixes had significant effects on all nutrient contents, except K (range, 61.3–144.8 mg·L^{-1}), chloride (range, 47.9–113.0 mg·L^{-1}), and S (range, 76.8–254.6 mg·L^{-1}) (Tables 9 and 10). The greatest NH_4 content

Table 5. Effects of 13 different potting mix ratios on soil nutrients of chrysanthemum 'Aduro Orange' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	NH_4 (mg·L^{-1})	NO_3 (mg·L^{-1})	P (mg·L^{-1})	K (mg·L^{-1})	Ca (mg·L^{-1})	Mg (mg·L^{-1})	S (mg·L^{-1})
Soilless media	100 soilless media	3.7 abc[ii]	177.8 a	130.2 a	101.8 bc	151.3 ab	129.1 a	594.1 ab
ERC bark	25 ERC bark:75 soilless media	5.3 a	174.9 ab	94.1 b	99.3 bc	166.0 a	127.1 ab	670.4 a
ERC bark	50 ERC bark:50 soilless media	3.4 abcd	31.3 c	40.7 cd	59.5 c	84.3 ab	57.6 abc	394.0 ab
ERC bark	75 ERC bark:25 soilless media	4.3 ab	36.5 c	35.6 cdef	113.8 abc	72.8 ab	47.0 bc	231.1 b
300–350	25 biochar:75 soilless media	3.5 abc	146.7 abc	42.1 c	106.5 abc	143.9 ab	109.0 abc	609.8 ab
300–350	50 biochar:50 soilless media	0.8 cde	87.6 abc	20.3 cdef	122.3 abc	94.2 ab	64.4 abc	513.8 ab
300–350	75 biochar:25 soilless media	0.4 e	99.5 abc	11.6 ef	166.0 ab	83.0 ab	56.7 abc	426.9 ab
400–450	25 biochar:75 soilless media	2.2 bcde	184.8 a	38.6 cde	130.8 abc	178.4 a	127.3 ab	681.4 a
400–450	50 biochar:50 soilless media	0.5 de	84.5 abc	20.0 cdef	151.0 abc	80.3 ab	62.7 abc	563.5 ab
400–450	75 biochar:25 soilless media	0.3 e	91.5 abc	10.2 f	203.5 a	64.9 ab	50.5 abc	400.4 ab
500–550	25 biochar:75 soilless media	2.7 abcde	135.9 abc	43.4 c	123.8 abc	108.0 ab	86.6 abc	518.6 ab
500–550	50 biochar:50 soilless media	0.5 de	38.8 bc	24.0 cdef	86.0 bc	39.5 b	31.1 c	337.5 ab
500–550	75 biochar:25 soilless media	0.4 e	34.0 c	14.3 def	129.5 abc	37.0 b	33.3 c	400.7 ab
Significance		<0.001	<0.001	<0.001	0.01	<0.001	<0.001	0.04

[i] ERC bark and biochar were from Eastern red cedar and biochar was made using the double barrel pyrolysis system; Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 4) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

Ca = calcium; K = potassium; Mg = magnesium; P = phosphorus; S = sulfur.

Table 6. Effects of 13 different potting mix ratios on soil nutrients of chrysanthemum 'Aduro Orange' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	pH	EC (μS·cm^{-1})	B (mg·L^{-1})	Cl (mg·L^{-1})	Na (mg·L^{-1})
Soilless media	100 soilless media	6.7 e[ii]	3400.0 abc	0.3 a	196.5 ab	357.0 a
ERC bark	25 ERC bark:75 soilless media	7.10 de	3530.5 ab	0.2 ab	232.5 ab	379.0 a
ERC bark	50 ERC bark:50 soilless media	7.5 bcd	1959.0 abc	0.2 cd	149.3 ab	234.4 ab
ERC bark	75 ERC bark:25 soilless media	7.5 bcd	1718.3 c	0.2 bcd	124.2 ab	152.6 b
300–350	25 biochar:75 soilless media	7.5 bcd	3232.5 abc	0.2 bcd	203.0 ab	357.8 a
300–350	50 biochar:50 soilless media	8.0 abc	2624.0 abc	0.2 bcd	171.0 ab	323.1 a
300–350	75 biochar:25 soilless media	8.1 ab	2670.0 abc	0.2 bcd	194.4 ab	308.8 ab
400–450	25 biochar:75 soilless media	7.3 cde	3642.5 a	0.2 bc	246.3 a	393.1 a
400–450	50 biochar:50 soilless media	8.0 abc	2695.5 abc	0.2 bcd	178.6 ab	331.4 a
400–450	75 biochar:25 soilless media	8.0 ab	2592.5 abc	0.2 bcd	212.4 ab	280.9 ab
500–550	25 biochar:75 soilless media	7.5 abcd	3007.5 abc	0.2 bcd	194.6 ab	364.5 a
500–550	50 biochar:50 soilless media	8.0 abc	1813.8 bc	0.1 d	118.3 b	259.8 ab
500–550	75 biochar:25 soilless media	8.2 a	2032.3 abc	0.1 d	152.3 ab	282.3 ab
Significance		<0.001	0.01	<0.001	0.03	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 4) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

B = boron; Cl = chloride; EC = electrical conductivity; Na = sodium.

was recorded with 50% v/v ERC bark, and it was similar to that observed with 100% v/v soilless media, 25% v/v ERC bark, and 25% v/v biochar at 300 to 350 °C. The nitrate level was greatest with 100% soilless media and was reduced with biochar at high temperatures and high rates. Similarly, the Ca and Mg contents decreased with the increasing rate of biochar at 500 to 550 °C. In contrast, 75% v/v biochar at 400 to 450 °C and at 500 to 550 °C had the greatest pH of all the media; it was increased by 26.98% compared with that observed with 100% v/v soilless media. Similar to Ca and Mg, the Na content in media decreased with increasing rates of biochar and ERC bark. The greatest B content was observed with 100% v/v soilless media and reduced up to 66.66% with 50% v/v biochar and 75% v/v biochar at 500 to 550 °C.

Discussion

Aeration increased and WHC decreased with the higher rate of biochar. Our results regarding biochar and media properties correspond with those of various studies (Githinji 2014; Mendez et al. 2015). Similar to our results, Mendez et al. (2015) reported increased air porosity when 50% deinking sludge biochar was added to brown peat; however, the air porosity decreased when it was added to coir. Githinji et al. (2014) also found an increase in porosity ranging from 10% to 56% with 25% to 100% peanut (*Arachis hypogaea* L.) hull biochar applications. Similar to our results, Vaughn et al. (2013) reported varied total porosity of media among treatments without a certain trend. In contrast to our results, Zhang et al. (2014) and Mendez et al. (2015) reported increased WHC with higher rates of deinking (50%) and coconut husk (35%) biochar. Differences between our study and others might be attributable to the particle size of biochar used. According to Jayasinghe (2012), large particle aggregates (>1 mm) lead to excessive aeration and reductions in WHC. Additionally, the 30-min time duration we used to determine the WHC of media might not have been sufficient for biochar because of its fine and complicated pore network (Kaudal et al. 2016). According to Dumroese et al. (2011), water will be absorbed more readily if exposed to biochar for a longer duration. Mendez et al. (2015) reported an increased bulk density of peatmoss with the addition of biochar produced at 300 °C, which corresponded with our results. However, a lower temperature made the biochar heavier compared with that observed at a higher temperature, thus increasing the weight of the blends used. This observation corresponded with the findings of Khanmohammadi et al. (2015), who studied sewage sludge biochar. The increased weight of blends consequently resulted in a reduction in the bulk density of the growing media.

Loss of volatile mass with increased pyrolysis temperatures resulted in greater ash contents in biochar (Jassal et al. 2015), similar to our results. Similarly, Ozcimen and

Table 7. Effects of 13 different potting mix ratios on the growth and plant quality of ornamental kale 'Fringed Nagoya Red' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	Ht (cm)	Width (cm)	Shoot dry wt (g)	Root dry wt (g)	WUE (mg·mL^{-1})	Root to shoot ratio (unitless)
Soilless media	100 soilless media	15.7 a[ii]	26.1 a	23.2 a	1.8 a	2.0 a	0.08 ab
ERC bark	25 ERC bark:75 soilless media	14.2 b	24.6 b	17.5 bcd	1.4 b	1.7 bc	0.07 ab
ERC bark	50 ERC bark:50 soilless media	11.6 d	22.3 cd	10.3 f	1.0 e	1.1 e	0.08 ab
ERC bark	75 ERC bark:25 soilless media	8.1 e	16.7 e	3.4 g	0.3 f	0.5 f	0.07 ab
300–350	25 biochar:75 soilless media	13.8 bc	23.8 b	16.7 cde	1.3 bc	1.6 cd	0.07 b
300–350	50 biochar:50 soilless media	12.2 d	23.4 bc	15.2 de	1.3 bcd	1.6 bc	0.07 b
300–350	75 biochar:25 soilless media	11.4 d	22.0 d	10.3 f	0.9 e	1.3 de	0.07 ab
400–450	25 biochar:75 soilless media	14.8 ab	24.0 b	19.6 b	1.4 b	1.9 ab	0.06 b
400–450	50 biochar:50 soilless media	12.5 dc	23.9 b	14.4 e	1.4 b	1.6 cd	0.06 b
400–450	75 biochar:25 soilless media	11.7 d	22.1 d	10.2 f	1.0 de	1.4 de	0.09 ab
500–550	25 biochar:75 soilless media	14.4 b	24.3 b	18.8 bc	1.4 bc	1.8 bc	0.08 ab
500–550	50 biochar:50 soilless media	12.4 dc	23.6 b	16.1 de	1.2 bcd	1.7 bc	0.06 b
500–550	75 biochar:25 soilless media	12.1 d	22.2 cd	10.5 f	1.1 cde	1.4 d	0.1 a
Significance		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 16) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

WUE = water use efficiency.

Table 8. Effects of 13 different potting mix ratios on leaf nutrients of ornamental kale 'Fringed Nagoya Red' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	TN (%)	Mg (%)	Mn ($mg \cdot L^{-1}$)
Soilless media	100 soilless media	4.5 a[ii]	0.6 a	119.8 ab
ERC bark	25 ERC bark:75 soilless media	4.0 ab	0.5 ab	108.9 ab
ERC bark	50 ERC bark:50 soilless media	4.1 ab	0.5 ab	114.3 ab
ERC bark	75 ERC bark:25 soilless media	3.8 ab	0.4 b	147.2 ab
300–350	25 biochar:75 soilless media	3.9 ab	0.6 ab	10.0 c
300–350	50 biochar:50 soilless media	4.0 ab	0.5 ab	161.5 a
300–350	75 biochar:25 soilless media	3.8 ab	0.5 ab	136.7 ab
400–450	25 biochar:75 soilless media	4.0 ab	Lost	Lost
400–450	50 biochar:50 soilless media	3.9 ab	Lost	Lost
400–450	75 biochar:25 soilless media	3.6 b	0.5 ab	148.6 ab
500–550	25 biochar:75 soilless media	4.2 ab	0.6 ab	97.1 b
500–550	50 biochar:50 soilless media	3.9 ab	0.5 ab	119.3 ab
500–550	75 biochar:25 soilless media	3.6 b	0.6 ab	159.4 a
Significance		0.05	0.05	<0.001

[i] ERC bark and biochar were from Eastern red cedar and biochar was made using the double barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 4) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$) according to the Tukey highly significant difference test.

Some samples were lost during the analysis.

Mg = magnesium; Mn = manganese; TN = total nitrogen.

Ersoy-Meriçboyu (2010) suggested that the greater ash content of biochar was attributable to the presence of mineral matter that persists as ash residue in biochar. The pH increased with increased pyrolysis temperature because of a loss of acidic functional groups like carboxyl and hydroxyl and carbonate formation (Chandra and Bhattacharya 2019; Clauston et al. 2014). Furthermore, Al-Wabel (2018) mentioned that conjugate bases form because of the deprotonation of acid groups, thus making biochar more alkaline. Specifically, Figueiredo et al. (2018) suggested that increased alkaline compound concentrations like Mg $(OH)_2$ and $Ca(OH)_2$ are responsible for the increase in the pH of biochar. The C content in biochar reached a peak at 400 to 450 °C and then became stable at higher temperatures, similar to the findings of Sun et al. (2014), who studied hickory (*Carya* sp. N.) wood and bagasse biochar.

The greatest plant growth and quality were observed with lower rates of biochar. Our results correspond with those of Fascella et al. (2018), who reported decreased plant height, flower numbers, shoot dry weight, and WUE of rose plants with 75% conifer wood biochar. Additionally, Fornes and Belda (2018) reported a reductions of 51% to 70% in root biomass and 11% to 30% in shoot biomass of tomato (*Lycopersicum esculentus* Mill) plant with 75% and 100% forest wood biochar. Similarly, Bhattarai et al. (2022) and Subedi et al. (2023) suggested that a biochar application rate less than 7.5% improves plant growth and quality of potted broccoli (*Brassica oleracea* var. *italica* Plenck.) and chilli (*Capsicum annuum* L.). In this study, as the biochar ratio increased from 25% to 75%, the pH of media increased, which might have caused a decrease in the total dry weight of the plant because of the decreased nutrient uptake (Graber et al. 2010). A high pH restricts nutrient uptake by elevating the root apoplastic pH and disturbing the pH gradient between membranes, thus causing a reduction in the nutrient levels of NO_3, P, and Mg (Xu et al. 2020). In addition to a high pH, there are various factors that influence plant growth and development. One of them is osmotic stress caused by high EC at a high biochar rate that leads to decreased plant growth and flower numbers (Conversa et al. 2015). Similarly, Samarakoon et al. (2006) reported that an increase in the uptake of higher-concentrated ions with high EC may hinder the uptake of ions present in lower concentrations, leading to nutrient imbalance and lower dry matter production. In addition to EC, a high rate of biochar also increases the C:N ratio; when the C:N ratio is greater than 30:1, microbes consume the available N for themselves and reduce the N availability for plants (Atkinson et al. 2010). The reason for the high C:N ratio can be attributed to an increase in the C content within biochar and a decrease in the mineralization fraction through the pyrolysis process, thus leading to N immobilization (Rajkovich et al. 2012). Additionally, the decreased flower number with a higher biochar rate (50%) might be caused by phytotoxicity of biochar and high pH, and the negative stress caused by a greater rate of biochar can be reduced by fertilization (Regmi et al. 2022). Additionally, Kammann and Graber (2015) reported that greater phytotoxicity caused by organic compounds and heavy metals present in biochar might be another reason for the reduced root dry weight of crops with a greater rate of biochar.

Starr et al. (2010) found no influence of the ERC bark rate on the chlorophyll content of potted Chinese pistache (*Pistacia chinensis* B.), similar to our findings. Various other biochars have had no significant effect on the chlorophyll content in beans (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.) (Quilliam et al. 2012; Sun et al. 2022), similar to our findings for both species. The high biochar and low moisture contents produced a stress effect on the leaves, resulting in smaller and thicker leaves, which accounted for similar chlorophyll contents in all plants (Zhang et al. 2022). However, other studies showed increased chlorophyll in plants such as

Table 9. Effects of 13 different potting mix ratios on soil nutrients of ornamental kale 'Fringed Nagoya Red' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	NH_4 ($mg \cdot L^{-1}$)	NO_3 ($mg \cdot L^{-1}$)	P ($mg \cdot L^{-1}$)	Ca ($mg \cdot L^{-1}$)	Mg ($mg \cdot L^{-1}$)
Soilless media	100 soilless media	5.0 abc[ii]	188.6 a	107.1 a	107.0 ab	98.0 a
ERC bark	25 ERC bark:75 soilless media	5.3 ab	181.9 ab	78.3 b	127.1 a	97.4 a
ERC bark	50 ERC bark:50 soilless media	6.9 a	58.8 abc	50.3 cd	95.4 ab	61.9 ab
ERC bark	75 ERC bark:25 soilless media	1.9 bcd	22.3 c	37.5 cdef	64.9 ab	34.8 ab
300–350	25 biochar:75 soilless media	3.2 abcd	157.8 abc	58.1 bc	101.2 ab	74.1 ab
300–350	50 biochar:50 soilless media	0.8 d	82.4 abc	31.5 def	51.9 ab	35.1 ab
300–350	75 biochar:25 soilless media	0.7 d	37.6 abc	15.6 f	28.8 b	18.0 b
400–450	25 biochar:75 soilless media	1.4 cd	119.6 abc	45.6 cde	65.2 ab	47.8 ab
400–450	50 biochar:50 soilless media	0.6 d	75.8 abc	22.7 ef	49.2 ab	34.1 ab
400–450	75 biochar:25 soilless media	0.3 d	37.9 abc	16.4 f	21.1 b	15.5 b
500–550	25 biochar:75 soilless media	1.7 bcd	143.1 abc	53.3 cd	83.5 ab	63.5 ab
500–550	50 biochar:50 soilless media	0.7 d	26.7 bc	37.8 cdef	20.7 b	14.6 b
500–550	75 biochar:25 soilless media	0.4 d	25.9 bc	23.3 ef	14.3 b	10.8 b
Significance		<0.001	<0.001	<0.001	<0.001	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).

[ii] Means (n = 4) within a column followed by same lowercase letter are not significantly different ($P \leq 0.05$).

Ca = calcium; Mg = magnesium; P = phosphorus.

Table 10. Effects of 13 different potting mix ratios on soil nutrients of ornamental kale 'Fringed Nagoya Red' grown in a greenhouse during Fall 2022 in Stillwater, OK, USA.

Temperature (°C)	Media ratio[i] (v/v)	pH	EC (μS·cm^{-1})	B (mg·L^{-1})	Na (mg·L^{-1})
Soilless media	100 soilless media	6.3 f[ii]	2493.3 a	0.3 a	242.8 a
ERC bark	25 ERC bark:75 soilless media	6.6 ef	2530.5 a	0.3 ab	220.0 ab
ERC bark	50 ERC bark:50 soilless media	7.2 bcd	1791.3 a	0.2 bcd	154.3 abc
ERC bark	75 ERC bark:25 soilless media	7.2 bcd	1189.0 a	0.2 cde	90.7 c
300–350	25 biochar:75 soilless media	7.0 de	2363.3 a	0.2 bc	221.2 ab
300–350	50 biochar:50 soilless media	7.5 abcd	1576.8 a	0.2 def	180.9 abc
300–350	75 biochar:25 soilless media	7.7 ab	1084.5 a	0.2 def	115.3 c
400–450	25 biochar:75 soilless media	7.3 bcd	1939.3 a	0.2 cde	218.9 ab
400–450	50 biochar:50 soilless media	7.7 abc	1730.8 a	0.2 cdef	183.7 abc
400–450	75 biochar:25 soilless media	8.0 a	1092.0 a	0.2 cdef	112.9 c
500–550	25 biochar:75 soilless media	7.1 cde	2209.5 a	0.2 cde	217.4 ab
500–550	50 biochar:50 soilless media	7.7 abc	1038.5 a	0.1 ef	161.9 abc
500–550	75 biochar:25 soilless media	8.0 a	1053.3 a	0.1 f	137.1 bc
Significance		<0.001	0.02	<0.001	<0.001

[i] ERC bark and biochar were from Eastern red cedar. Biochar was made using the double-barrel pyrolysis system. Soilless media comprised BM7 45% v/v bark (Berger, Saint-Modeste).
[ii] Means (n = 4) within a column followed by the same lowercase letter are not significantly different ($P \leq 0.05$).
B = boron; EC = electrical conductivity; Na = sodium.

cowpea (*Vigna unguiculate* L.) and calendula (*Calendula officinalis* L.) with biochar applications compared with untreated plants (Farooq et al. 2020; Karimi et al. 2020).

The application of ERC bark with a rate greater than 50% reduced plant growth and quality. A similar result was reported by Brown and Emino (1981), who reported that 80% cedar chips with 20% perlite resulted in the lowest dry weight and height of tomatoes and polka dot plant (*Hypoestes phyllostachya* B.) compared with 50% ground bark with 50% vermiculite and 40% composted bark with 40% peat. Reduced plant height, shoot, and root dry weight and flowering of the plant might be caused by the greater air porosity present in 75% ERC bark, which lead to the poor water holding capacity of media (Starr et al. 2010). Lower plant growth with 75% ERC bark could also be explained by the lower water content with the treatment (Amoroso et al. 2010). Because a higher rate of cedar ERC bark reduced plant growth and quality, Fox (1979) suggested preplant composting and leaching before its use as a mix for growing short-term crops.

The EC and P concentrations of growing media decrease with higher rates of biochar after harvesting. Our results corresponded with those of Chrysargyris et al. (2020), who reported a decrease in EC of media with two commercial biochar applications at 7.5% and 15% because of the greater EC of soilless media that we used compared with that of the biochar. Prasad et al. (2018) also reported decreases in EC and P with the addition of 50% wood chips biochar and with 25% paper fiber biochar. Dispenza et al. (2016) and Chrysargyris et al. (2020) also reported increasing pH and a reduced P concentration of growing media with the increased rate of conifer wood biochar. After harvesting, NH_4 and NO_3 concentrations decreased with the higher rate of biochar, similar to the results of Margenot et al. (2018).

Similar to our findings, Altland and Locke (2012) reported decreased Ca and Mg concentrations and an increased K concentration in growing media with increasing rates of rice hull biochar from 10% to 30%. Additionally, Chrysargyris et al. (2020) reported decreased Mg and S concentrations in growing media with the addition of forest wood biochar. An increased K concentration in the media with biochar application in media could be caused by the ion adsorption capacity with higher mobility because of the biochar pore structure (Chen et al. 2018). With an increasing rate of bamboo (*Bambusa vulgaris* Schrad. ex J.C. Wendl) biochar from 25% to 50%, the concentrations of Ca and Mg decreased, which can be explained by the antagonistic behavior of Ca, Mg, and K (Farrar et al. 2021; Rhodes et al. 2018). A decreased Na concentration in media with the high rate (30 t·ha^{-1}) of bamboo biochar corresponded to the findings of (Farrar et al. 2021). The decreased Na might be attributable to the replacement of Na by Ca at the exchange site of the soil solution (Rajkovich et al. 2012).

There was no significant difference in the K and Na concentrations of ornamental kale. However, for chrysanthemum, significant differences in K and Na were observed. The TN, P, K, and Ca concentrations of chrysanthemum were within the recommended values for leave concentrations, but the iron concentration was lower (Uchida 2000). Fascella et al. (2018) reported a decrease in the foliar P concentration in rose plants when the biochar rate increased to 50% and 75%, which corresponded to our results for chrysanthemum. Farrar et al. (2021) reported that the Mg concentration in ginger (*Zingiber officinale* R.) leaves was greatest with soil without the biochar amendment, similar to our findings with 10% soilless media. This difference suggested that the impact of biochar on the foliar nutrient concentration may differ between plant species (Hairani et al. 2016).

The biochar particle size used during our research ranged from 2 mm to 20 mm. In addition to the rate and temperature, the biochar size also affects the plant growth; fine (60 mesh) and medium (30 mesh) biochar resulted in better results and higher available N and P concentrations compared with those observed with coarse (10 mesh) biochar (Gu et al. 2022; Sarfraz et al. 2020). The increase in P availability might be attributable to the greater surface area and greater particle destruction of smaller particle sizes (Sarfraz et al. 2020). Additionally, the higher water retention capacity of smaller biochar (0.5 mm) with a greater surface area might be another reason for better plant growth compared with that of larger biochar (4 mm) (Liao and Thomas 2019). However, another study suggested that biochar particles that are too fine reduced the hydraulic conductivity of media by binding soil aggregates together (Ouyang et al. 2013).

Our study and those of others had differing production processes, biomass sources, and crops. In contrast to other studies that used grind mulch and biochar (Blok et al. 2017; Sarfraz et al. 2020), we used the form readily available. Moreover, our double-barrel system of producing biochar differs from other systems that use ovens for biochar production or commercially available biochar. Additionally, it is crucial to note that a single growing media is not universally suited for all crops, resulting in diverse outcomes of various experiments.

Conclusion

In this study, the plant growth and WUE of ornamental kale were greatest with 100% soilless media; however, with 25% biochar at 400 to 450 °C, the WUE was not significantly different. For chrysanthemum, as the biochar rate increased from 25% v/v, plant growth, flowering, and WUE decreased. For both chrysanthemum and ornamental kale, 75% ERC bark reduced plant growth and quality; this might have been caused by the greater air porosity and poor WHC of the media mixed with ERC bark. For both plants, greater biochar rates (>25%) were detrimental to plant growth. The larger size of the mulch reduced the interaction of plant roots and growing media because of the larger space between particles. Additionally, based on volume, 75% mulch occupies less space compared with 75% biochar because of its larger size covering more volume with a small amount. This hinders plant root development and ultimately reduces plant performance. Therefore, using ground mulch is preferable to larger alternatives. Regarding the growing media, air porosity increased and WHC decreased with greater biochar rates. Biochar at a rate less than 25% can be used as a supplement for peatmoss during greenhouse production of chrysanthemum, but not for ornamental kale. The reduction in plant performance can be attributed to increased air porosity of the media caused by larger biochar particles and, possibly, the high pH level. To address this problem, smaller biochar particles and reducing the pH at a greater biochar rate by applying sulfate or aluminum sulfate are recommended. The particle size of biochar was larger than that used for other greenhouse studies; therefore, future research should evaluate whether grinding the ERC biochar into smaller pieces would allow for better plant growth.

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