HortScience 58(9):1035–1044. 2023. https://doi.org/10.21273/HORTSCI17257-23

Greenhouse Cultivation of Cucumber (*Cucumis sativus* L.) in Standard Soilless Media Amended with Biochar and Compost

Sujatha Venkataramani and Arjun Kafle
Department of Plant and Soil Science, Texas Tech University, Lubbock, TX 79409, USA

Manpreet Singh
Department of Plant and Soil Science, Texas Tech University, Lubbock, TX 79409, USA, and Kearney Agricultural Research and Extension Center, University of California Agriculture and Natural Resources, Parlier, CA 93648, USA

Sukhbir Singh, Catherine Simpson, and Matthew G. Siebecker
Department of Plant and Soil Science, Texas Tech University, Lubbock, TX 79409, USA

Keywords. growth, peat, physiology, substrate, sustainability

Abstract. **Peat is one of the most commonly used substrates in soilless cultivation. However, peat mining produces a negative carbon footprint, which raises the need for alternative sustainable substrate media. To address this, we studied the impact of peat replacement with a combination of various biochars and cotton burr compost on the growth and yield of cucumber (*Cucumis sativus* L.), and nutrient concentration of media, plant leaf, and fruit in greenhouse conditions. Two experiments were conducted from Nov 2020 through Jan 2021 (Trial 1) and from Feb to Apr 2021 (Trial 2). The treatments were control (peat, vermiculite, and perlite at 2:1:1) and in the control peat was either fully replaced (hardwood biochar+compost, softwood biochar+compost, and hemp biochar+compost) or partially replaced up to 50% (v/v) (hardwood biochar+compost, softwood biochar+compost, and hemp biochar+compost). The control media was more acidic with lowest electrical conductivity than the other treatments. The leaf chlorophyll content and the photosynthetic assimilation rate varied among the treatments in both trials. The final dry shoot biomass was lowest in peat-dominated control treatment suggesting biochar-compost in the substrate media contributed in increased dry biomass of the cucumber plant. The total number of fruits per plant and total yield per plant was significantly increased in all the treatments with the highest in hardwood biochar+compost, compared with the control. The nutrient concentration of media, leaf, and fruit indicates that biochar-compost enhances the nutritional status of the media, which supplies essential nutrients to the plant leaf and fruit while growing in different substrate compositions. Our results suggest that the replacement of peat with full or partial proportions of biochar-compost can produce similar and, in some cases, even better growth, yield, and physiology in potted cucumber than in the unamended control treatment.**

Soilless substrates are the mainstay of container production and nursery industries of horticultural plants. Peat moss is a primary component of many commercial soilless growing media due to its desirable properties, such as high porosity, low bulk density, high water-holding capacity, and nutrient exchange capacity (Savvas and Gruda 2018). In 2019, the United States consumed 1.6 million tons of peat, of which 70% of domestic consumption was imported from Canada [US Geological Survey (USGS) 2020]. Because peatlands are a net carbon sink, peat mining could create an imbalance in the carbon budget. The cost factor in peat use poses another serious challenge owing to the competing uses, the high cost of the extraction process, and transportation (Carlile et al. 2015). Concerns regarding the conservation of wetland ecosystems and climate change have propelled many countries, including the United States and several European countries, to plan the elimination or reduction of the use of peat by 2025–35 (USGS 2020). Therefore, sustainable alternatives are needed to substitute peat in the growing media. These substitutes should be environmentally friendly, cost-effective, sustainable, and used for the long term (Najarian and Souri 2020). Different organic materials and farm waste products that have been investigated as potential substitutes for peat include coconut coir, sawdust, bark, compost, and biochar (Álvarez et al. 2018). Some of these alternatives have several advantages over peat, but they also have some limitations. Coir has greater leaching of nitrogen (N) and poor water-holding capacity and tends to have more natural salts (Prasad 1997), although coconut coir has been extensively used. Bark is not rich in N and may cause manganese (Mn) toxicity that can be detrimental to plants (Gruda 2019; Maher and Thomson 1991). The sawdust, wood fibers, or chips that come from woodworking industries are characterized by low water retention capacity and may contain phytotoxins (Gruda 2019). It may be for these reasons that these substrates are less used. Compost, however, is a good growing medium constitute because it is a rich source of fiber and essential nutrients that promote plant growth (Gruda 2019). It has high organic matter, nutrient content, and most importantly, it provides for safe reuse of waste products (Abdel-Razzak et al. 2019). Most of the studies with compost at 20% to 40% substitution (% v/v) were reported to have enhanced roots and shoot growth with no side effects in the soilless media cultivation (Belda et al. 2013).

Another promising alternative substrate in soilless media is biochar. Biochar is a carbon-rich coproduct of organic matter pyrolysis that, unlike charcoal, is intended to be used as a soil amendment (Álvarez et al. 2018) with many advantages (Ebrahimi et al. 2021). Biochar amendment effects on soil physical and chemical properties and on plant growth under soil-based cultivation have been extensively examined (Manirakiza and Şeker 2020; Song et al. 2020; Zheng et al. 2020). Biochar has recently got attention as a replacement candidate for peat (Sabatino et al. 2020) because of its low bulk density, high porosity, high water and nutrient retention, and high consistency (Savvas and Gruda 2018). However, less information is available on its performance as a soilless substrate in plant-growing media. Interestingly, it has been reported that a combination of biochar and compost can be a viable growing medium (Schmidt et al. 2014). Many studies employing biochar in peat-based growing media demonstrated negative, neutral, and positive effects on plant growth by altering nutrient absorption, porosity, and water-holding capacity of media (Chrysargyris et al. 2019; Margenot et al. 2018). The contrasting results of biochar amendment can be attributed to its chemical and physical properties which may vary with feedstock and pyrolysis conditions. For instance, a replacement of peat with softwood biochar (70% of total volume) has been tested without any adverse effects on marigold (*Tagetes erecta* L.) production (Margenot et al. 2018), although 100% peat replacement with green waste biochar reduced the growth

Received for publication 19 May 2023. Accepted for publication 24 Jun 2023.
Published online 18 Aug 2023.
We express our sincere thanks to Dr. Reynaldo Patiño for his valuable suggestions to improve this manuscript. We are grateful to Dr. Vikram Baliga, Mr. Kamron Newberry, Dr. Azeezahmed Shaik, and the staff of the Horticulture Gardens and Greenhouse Complex for their help during the experiments. We are also thankful to the Department of Plant and Soil Science, Texas Tech University for providing the resources to complete this study.
S.S. is the corresponding author. E-mail: s.singh@ttu.edu.

of *Calathea rotundifola* cv. *Fasciata* (Tian et al. 2012).

A full replacement of peat incurring high biochar rates in growing media may not be conducive to plant growth and development because high pH and salt content (ash) in biochar may cause osmotic stress in plants (Steiner and Harttung 2014). There is evidence that the combination of biochar and compost has the potential to be a partial substitute for peat in growing media (Álvarez et al. 2018). However, based on the literature review, information is limited regarding the full replacement of nonrenewable peat with a biochar and compost mixture. We hypothesized that biochar and compost mixture could serve as a recyclable and renewable alternative to peat in the growing media.

Cucumber is one of the most widely grown vegetables in the world. The global production of cucumbers was nearly 75 million tons in 2018, with countries such as the United States, European countries, India, China, and Turkey producing them across ~2 million hectares (Food and Agricultural Organization 2018). The US production of cucumbers averaged 590 million kg in 2020, and greenhouse production was 23,000 tons. One of the reasons for the reduced production of greenhouse vegetables is due to soilborne root diseases, which can be resolved by changing to soilless growing media production (El Sharkawi et al. 2014). Although general greenhouse soilless media includes peatmoss, it is a finite resource that is being depleted. Furthermore, given the cost of peat mining from the perspectives of both transportation and the environment, it is beneficial to consider peat replacement strategies with more renewable and local sources of substrates. Therefore, the purpose of this project was 1) to investigate the impact of peat replacement with a combination of various biochars and cotton-burr compost on the physiology, growth, and yield of cucumber in a greenhouse substrate container production system and 2) to assess the effect of different substrate combinations on the nutrient concentration of media, plant leaf, and fruit.

Materials and Methods

Growing conditions and planting material

Two experimental trials were conducted from Nov 2020 through Jan 2021 (Trial 1) and from Feb to Apr 2021 (Trial 2). Both trials were conducted in a greenhouse at the Horticulture Gardens and Greenhouse Complex, Texas Tech University, Lubbock, TX, USA. Throughout the growing season in both trials, the temperature, relative humidity, and photosynthetically active radiation were maintained at 25 °C day/20 °C night, 38%, and 147 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. No additional light was used. Seeds of cucumber hybrid 'Picolino' (Johnny's Selected Seeds, ME) were planted in plug trays using commercially available potting mix BM7 (Berger, Saint-Modeste, Canada). Plants were allowed to grow until the second true leaf stage (14 d after sowing) before transplanting to experimental treatments in 14-L pots with one plant per pot. All experimental plants were fertigated (by volume basis) every day starting 1 week after transplanting with of Jack's professional fertilizer with 20N–20P–20K (JR Peters Inc., Allentown, PA, USA) in a 1-L solution to let the transplant establish in the new growing environment and avoid transplanting shock. The electrical conductivity (EC) of the fertigation solution was maintained at 2 dS/m (1280 ppm) using portable Orion Star™ pH and EC meter (ThermoFisher Scientific, Waltham, MA, USA). Once flowering [28 days after planting (DAP)] was initiated, Jack's professional blossom booster fertilizer with 10N–30P–20K (JR Peters Inc.) was used at the same concentration of 1280 ppm. During Trial 2, there was a severe infestation of spider mites and aphids, which drastically affected the cucumber plants. To control the pest, Scorpion insecticide (Scorpion 35SL; Gowan Company, Yuma, AZ, USA) at a rate of 365 mL/ha was sprayed two or three times throughout the cropping period.

Soilless media treatments

The peat substrate Berger BM6 (Coarse peatmoss 85% and Horticultural Perlite 15%) was used to make standard media (Berger). Cotton-burr compost was obtained from Back to Nature (Slaton, TX, USA). Three types of biochar used in this study were hardwood, softwood, and hemp biochar. Hardwood (oak tree) and softwood (pine tree) biochar were purchased from Wakefield Agricultural Carbon LLC (Columbia, MO, USA). The physicochemical properties of these two types of biochars have previously been reported in Singh et al. (2022). The hemp biochar was prepared by combusting the dried hemp residue in a limited oxygen supply for 24 h in a 208-L capacity steel drum and was hammered to obtain fine particle biochar. Seven treatment combinations were randomized seven times in a Latin square design (Table 1). The design was chosen due to the presence of shadow variation from two sides of the experimental area. The standard peat–perlite–vermiculite (50:25:25) growing media was used as the control treatment. Perlite and vermiculite were kept constants for all the treatments, and except control, peat was either completely [full hardwood (FHW), full hemp (FH), and full softwood (FSW)] or partially [partial hardwood (PHW), partial hemp (PH), and partial softwood (PSW)] replaced with biochar and compost mixtures (Table 1).

Media EC and pH measurements

The EC and pH of the media were measured biweekly starting at 5 DAP for Trial 1 and 7 DAP for Trial 2. The collection plates were placed underneath the pots for these measurements. The pots were first irrigated to saturation. After ~1 h of irrigation, 500 mL of water was again added to the pot to collect the leachate for 30 min. The EC and pH were measured on the leachate of all plates using the portable Orion StarTM pH and EC meter (ThermoFisher Scientific).

Plant growth, physiological, and yield parameters

The plant height was measured from the base to the tip of the plant at 2-week intervals. The chlorophyll content was measured by MC-100 Apogee chlorophyll concentration meter (Apogee Instruments, Logan, UT, USA) and the net photosynthesis rate (P_n) was measured using the portable photosynthesis system (Model LI-COR 6800; LI-COR Biosciences, Lincoln, NE, USA) from the third or fourth sun-lit, young, fully expanded leaf at 2-week intervals. Cucumbers were picked at 2- to 3-d intervals when the fruit attained marketable size. The number of fruits and fruit weight per plant were recorded at each harvest and summed to obtain the total yield. At the end of each trial, the plants were oven-dried at 72 °C to a constant weight to determine the aboveground vegetative dry biomass. All these parameters were recorded from all seven replicates.

Nutrient analyses

Nutrient analysis of media. For nutrient analysis of media, 5 g of media samples from four replications were oven-dried overnight at 72 °C. The samples were then ground using mortar and pestle to pass through a 50-micron sieve. The sieved samples were subjected to X-ray fluorescence (XRF) using portable handheld Olympus Vanta pXRF (Olympus®, Waltham, MA, USA) to determine elemental concentrations. This method has been widely used for soil elemental analysis and documented in scientific literature (Ravansari et al. 2020; Weindorf et al. 2012). Each sample was packed into a vial to its maximum capacity/volume. The vial was covered with Prolene X-ray film (Chemplex Industries Inc., Palm City, FL, USA) and placed on the pXRF aperture. Fluorescence detection was achieved through an ultra-high resolution (<165 eV) silicon drift detector. The pXRF was standardized/calibrated using stainless steel "316" alloy dip clip containing 16.130% Cr, 1.780% Mn, 68.760% Fe, 10.420% Ni, 0.200% Cu, and 2.100% Mo, which was tightly fitted over the aperture. The instrument was operated under a proprietary configuration called Geochem Mode, which features quantitative analysis of the elements V, Cr, Fe, Co, Ni, Cu, Zn, Hg, As, Se, Pb, Rb, Sr, Zr, Mo, Ag, Cd, Sn, Sb, Ti, Mn, P, S, Cl, K, and Ca. The samples were scanned for a total of 4 min with two different

Table 1. The substrate composition of different types of soilless media used in cucumber experiments at Lubbock, TX, USA.

Soilless media type	Substrate composition BC-C-SP-P-V (%v/v)
Control	0-0-50-25-25
Full hardwood (FHW)	25-25-0-25-25
Full hemp (FH)	25-25-0-25-25
Full softwood (FSW)	25-25-0-25-25
Partial hardwood (PHW)	12.5-12.5-25-25-25
Partial hemp (PH)	12.5-12.5-25-25-25
Partial softwood (PSW)	12.5-12.5-25-25-25

BC = biochar; C = compost; SP = sphagnum peat moss; P = perlite; V = vermiculite.

X-ray beams, 1 and 2, each for 120 s. To validate the accuracy of pXRF before media scanning, an Olympus stainless calibration coin, a blank sample (pure SiO2), and two standard reference materials (SRM 2702—Inorganics in marine sediment, SRM 2781—Domestic Sludge) from the National Institute of Standards and Technology (NIST) were used.

Nutrient analysis of plant leaf. A similar procedure using the XRF technique was performed to analyze the nutrient concentrations of leaves. The leaf samples were taken from the second-fourth leaf for all treatments using seven replications. For the plant leaf samples, three NIST standard reference materials apple leaves (SRM 1515—Apple leaves, SRM 1547—Peach leaves, and SRM 1575—Pine Needles) were used. There are reports where pXRF technique has been used in determining the mineral nutrients in plant leaves (McLaren et al. 2012; Tadeu Costa et al. 2020).

Nutrient analysis of fruit. Three to four slices of cucumber fruit measuring ∼2.5 cm in diameter, including the peel, were cut from the central part of the fruit and stored at freezing temperature (–20 °C) from all replications. The samples were then freeze-dried for 2 to 3 d in a freeze dryer (Harvest Right, Salt Lake City, UT, USA). The freeze-dried samples were kept at –80 °C until they were ready to be grounded in a mortar and pestle using liquid nitrogen. The powdered samples were oven-dried at 72 °C overnight as a precautionary measure to remove any moisture. The pXRF technique described above in leaf nutrient analysis was used for the nutrient analysis of fruits.

Statistical analysis

Data for each parameter was analyzed using analysis of variance with the Latin square design in R version 3.5.2 using Agricolae package version 1.2-8. Data for each trial were analyzed separately. The differences among the means were compared using the least significant difference (LSD) test with a 0.05 level of significance. SigmaPlot version 14 (Systat Software, San Jose, CA, USA) was used to create graphs.

Results

Media EC and pH

The EC of the media treatments recorded over the two growing seasons is listed in Table 2. Before the start of fertigation, the control media had the lowest EC of 0.24 and 0.17 dS/m, and FH treatment had the highest EC of 6.05 and 6.67 dS/m in Trials 1 and 2, respectively, respectively (Table 2). After fertigation, the EC values started increasing and became higher toward the end of the growing season for all the treatments except FH in Trial 2. On average, the respective EC values of control, FSW, FHW, PH, PSW, and PHW were 22.3, 1.2, 1.4, 1.1, 2.5, and 2.4 times greater at the end of the trials compared with the beginning. This shows that EC increased as the growing season proceeded. Softwood biochar (FSW or PSW) showed a higher EC than hardwood biochar (FHW or PHW) for most of the observation dates in both trials because of higher initial EC. Similarly, FH and PH also maintained high EC values throughout the growing season. The full replacement of peat treatments (FH, FSW, and FHW) maintained greater EC than the partial replacement of peat treatments (PH, PSW, and PHW) at most of the observation dates in both trials. There was a considerable variation in media pH over the growing period in both trials (Table 3). The control treatment had the lowest pH while the FH treatment had the highest pH at most of the observation dates in both trials. The pH decreased with time in all the media treatments. On average, the respective pH values of control, FH, FSW, FHW, PH, PSW, and PHW were reduced by 5%, 17%, 21%, 17%, 24%, 22%, and 20% at the end compared with the beginning of the trials. The decrease in pH was larger in hemp biochar-compost-amended treatment than in the control. The full replacement of peat treatments (FH, FSW, and FHW) maintained higher pH than partial replacement of peat treatments (PH, PSW, and PHW) in both trials.

Table 2. Electrical conductivity (EC) measurements (± SD) of different media used in cucumber experiments at Lubbock, TX, USA.

	Media	EC (dS/m)			
Trial 1		5 DAP	27 DAP	41 DAP	54 DAP
	Control	0.24 ± 0.05	1.75 ± 0.21	4.05 ± 1.10	4.57 ± 1.00
	FHW	2.54 ± 0.43	3.98 ± 0.50	5.34 ± 0.18	6.31 ± 0.61
	FH	6.05 ± 0.75	4.59 ± 0.47	4.66 ± 0.31	6.67 ± 0.92
	FSW	2.87 ± 0.25	3.94 ± 0.20	5.71 ± 1.01	7.58 ± 1.28
	PHW	1.39 ± 0.19	3.31 ± 0.27	4.02 ± 0.85	4.31 ± 1.07
	PH	3.34 ± 0.34	3.40 ± 0.01	6.10 ± 0.06	5.68 ± 0.20
	PSW	1.66 ± 0.22	3.68 ± 0.24	4.88 ± 1.46	6.15 ± 1.36
Trial 2		7 DAP	23 DAP	39 DAP	55 DAP
	Control	0.17 ± 0.02	1.62 ± 0.42	3.08 ± 0.31	4.71 ± 0.61
	FHW	2.37 ± 0.27	3.12 ± 0.36	3.80 ± 0.41	5.69 ± 0.85
	FH	6.70 ± 1.80	5.98 ± 1.16	4.93 ± 0.73	5.69 ± 1.31
	FSW	3.01 ± 0.54	3.65 ± 0.29	4.53 ± 0.68	5.76 ± 1.72
	PHW	1.29 ± 0.42	2.62 ± 0.14	3.89 ± 0.79	4.81 ± 0.70
	PH	2.38 ± 0.32	2.69 ± 0.39	4.03 ± 0.46	5.71 ± 1.05
	PSW	1.63 ± 0.62	2.28 ± 0.09	4.06 ± 0.63	5.38 ± 1.53

N = 4 for each treatment. DAP = days after planting; FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

Plant growth, physiological and yield parameters

Plant height. The plant height remained comparable among media treatments for the first two observation dates in both trials (Fig. 1A and B). At 40 DAP, compared with control, all the treatments produced significantly taller plants in Trial 1 (Fig. 1A). FH, FSW, FHW, PH, PSW, and PHW had comparable plant heights at 40 DAP in Trial 1. However, plants were significantly taller only in FSW, PSW, FH, PH, and PHW treatments compared with FHW and control at 40 DAP in Trial 2 (Fig. 1B). Only PHW had significantly taller plants compared with FHW at 40 DAP in Trial 2. A similar trend was observed at the last observation date of 50 DAP and 55 DAP in Trial 1 and Trail 2, respectively. At the end of the growing season in Trial 1, plant height increased by 43%, 46%, 57%, 55%, 43%, and 30% in FH, FSW, FHW, PH, PSW, and PHW, respectively compared with control. In Trial 2, the increase in plant height at the end of the growing season was less than Trial 1. The observed plant height increases were 22%, 41%, 11%, 16%,

Table 3. The pH measurements (± SD) of different media used in cucumber experiments at Lubbock, TX, USA.

	Media	pH		
Trial 1		27 DAP	41 DAP	54 DAP
	Control	4.9 ± 0.01	4.7 ± 0.16	4.6 ± 0.09
	FHW	7.5 ± 0.44	6.5 ± 0.44	6.4 ± 0.97
	FH	8.5 ± 0.27	7.6 ± 0.57	7.4 ± 0.19
	FSW	7.3 ± 0.77	6.5 ± 0.40	6.0 ± 0.11
	PHW	7.0 ± 0.50	6.1 ± 0.34	6.0 ± 0.30
	PH	8.4 ± 0.01	7.2 ± 0.14	6.4 ± 0.45
	PSW	6.6 ± 0.30	5.8 ± 0.15	5.3 ± 0.30
Trial 2		23 DAP	39 DAP	55 DAP
	Control	4.7 ± 0.14	5.0 ± 0.16	4.4 ± 0.13
	FHW	7.9 ± 0.15	7.0 ± 0.41	6.4 ± 0.16
	FH	8.7 ± 0.15	7.7 ± 0.58	6.9 ± 0.37
	FSW	7.7 ± 0.41	6.3 ± 0.60	5.8 ± 0.33
	PHW	7.1 ± 0.25	5.6 ± 0.23	5.2 ± 0.15
	PH	7.8 ± 0.18	6.3 ± 0.42	5.8 ± 0.58
	PSW	7.1 ± 0.19	5.9 ± 0.26	5.4 ± 0.28

DAP = days after planting; FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

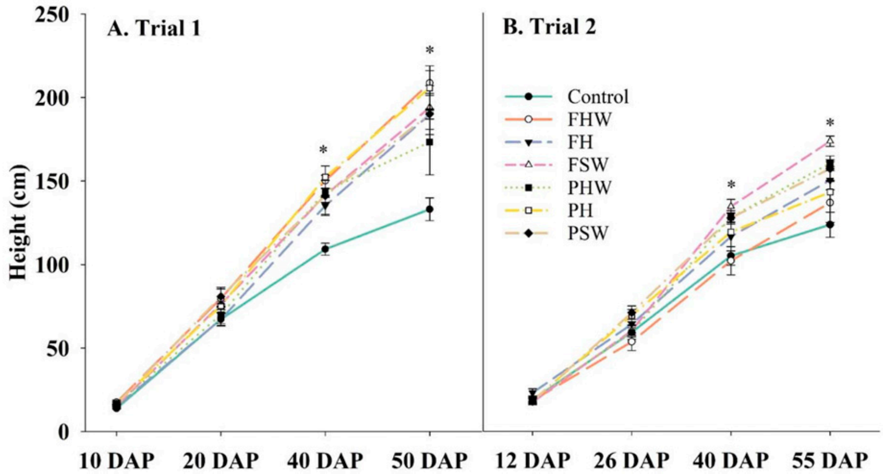

Fig. 1. Plant height of cucumber in (**A**) Trial 1 and (**B**) Trial 2 at Lubbock, TX, USA. Bars indicate standard error. *Significant difference at $P \leq 0.05$. DAP = days after planting; FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

27%, and 30% in FH, FSW, FHW, PH, PSW, and PHW, respectively compared with control. Although all treatments show taller plants, there was no direct relation in increase between full and partial doses of biochar-compost. It seems that there is no systematic effect of biochars-compost proportion on height for cucumber plants.

Chlorophyll content and Pn. In Trial 1, the control had the lowest chlorophyll content compared with other treatments for the first two measurements at 27 DAP and 38 DAP, respectively (Fig. 2A). FH recorded the highest chlorophyll content comparable with FSW and PH. FSW, PH, and PSW shared similar chlorophyll content PH and PSW, although had comparable chlorophyll content with FHW and PHW but FSW was significantly higher than FHW and PHW chlorophyll content at 27 DAP. At 38 DAP, there was a drastic reduction in chlorophyll content in FHW and FH in Trial 1 with other treatments chlorophyll content remaining similar or increasing slightly (Fig. 2A). It was interesting to observe that the chlorophyll content drastically increased at 52 DAP in the control plants compared with plants in other treatments. Control had similar chlorophyll content with FSW but significantly higher than other biochar-compost treatments. FHW and FH showed the lowest chlorophyll content at 52 DAP in Trial 1. The chlorophyll content was higher at 52 DAP than 27 DAP for most of the treatments, except FHW and FH. In Trial 2, the chlorophyll content had a different trend compared with Trial 1. In Trial 2, except control, chlorophyll content of all treatments started to increase from 27 DAP to 38 DAP and then reduced at 52 DAP (Fig. 2B). At 27 DAP, FHW had the highest chlorophyll content with comparable measurements in control, and FSW. FH, PH, and PSW had the lowest chlorophyll concentration at 27 DAP. Although FHW had the highest chlorophyll content at 27 DAP compared with other treatments, the rapid degradation of chlorophyll started after 38 DAP and reached the lowest at 52 DAP in Trial 2. There was an increase in chlorophyll content in FH, FSW, PHW, PH, and PSW at 38 DAP but rapidly decreased at 52 DAP with the least chlorophyll content in FHW, FH, and FSW at 52 DAP in Trial 2. The control showed the same pattern of increase in Trial 2 as in Trial 1. If we look at both the trials, the partial replacement peat with biochar-compost amendments maintained higher chlorophyll content than full replacement for most of the observations.

The plant showed an inconsistent rise and fall in *Pn* in Trial 1 (Fig. 2C). A significant difference in *Pn* was observed at the beginning (11 DAP), and later in the growing season (52 DAP). At 11 DAP, both the partial replacement treatments PHW and PSW maintained higher *Pn* compared with other treatments. However, as growth proceeded, control had the greatest *Pn* at 52 DAP. All the biochar-amended treatments had significantly lower *Pn* compared with the control at 52 DAP. Unlike Trial 1, *Pn* had a decreasing pattern in Trial 2 (Fig. 2D). A significant difference in *Pn* was obtained at 45 DAP, where control outperformed all the biochar-amended treatments. The reduction in *Pn* was rapid in the control from 45 DAP to 58 DAP (13 d period).

Dry biomass, fruit number, and yield. Plant dry biomass, the total number of fruits per plant, and fruit yield in both trials are presented in Fig. 3, respectively. All the biochar-compost-amended treatments had greater dry biomass than the

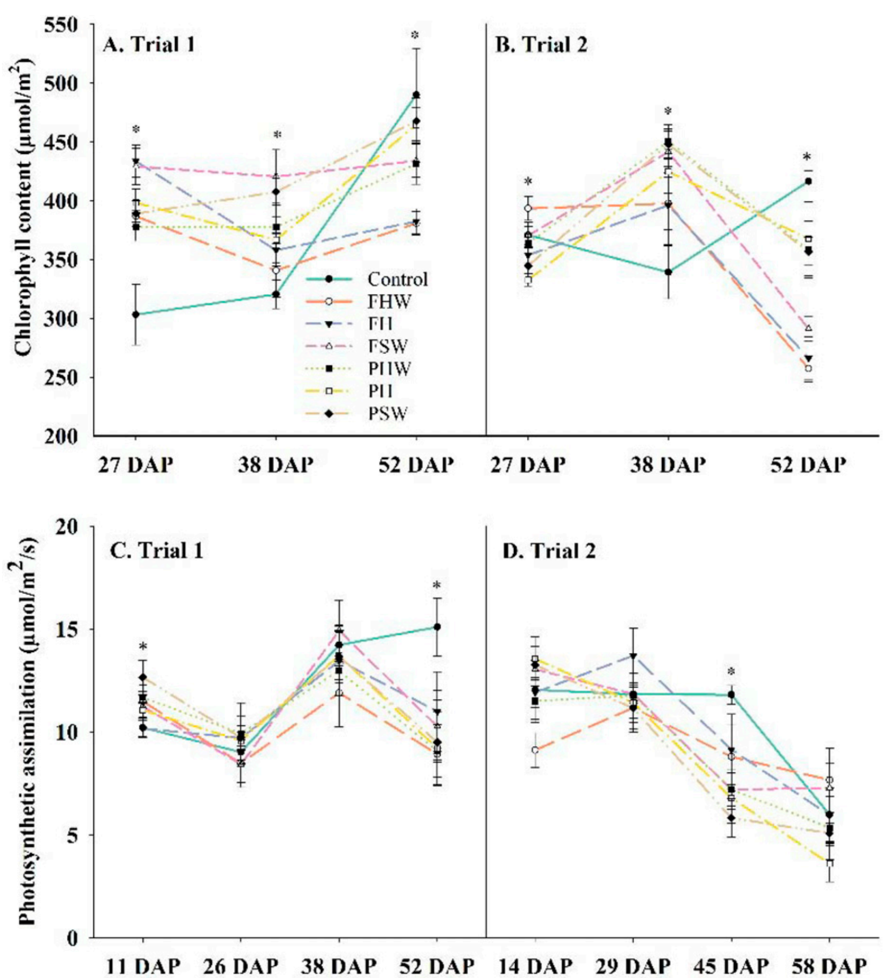

Fig. 2. Chlorophyll content of cucumber in (**A**) Trial 1 and (**B**) Trial 2, and photosynthetic assimilation (*Pn*) of cucumber in (**C**) Trial 1 and (**D**) Trial 2 at Lubbock, TX, USA. Bars indicate standard error. * Significant difference at $P \leq 0.05$. DAP = days after planting; FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

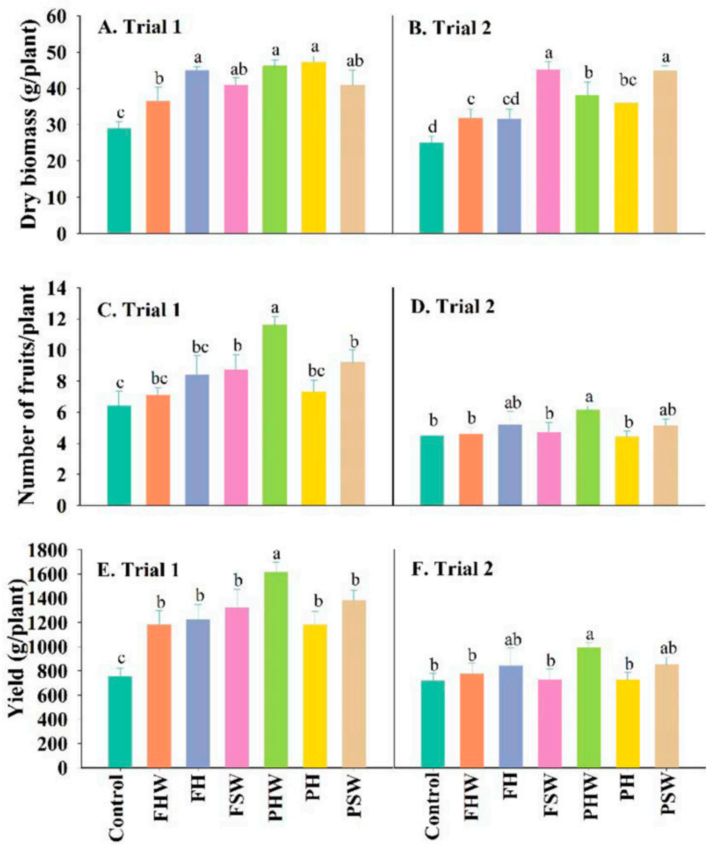

Fig. 3. Dry biomass/plant in (**A**) Trial 1 and (**B**) Trial 2, number of fruits/plant in (**C**) Trial 1 and (**D**) Trial 2, and the total yield/plant in (**E**) Trial 1 and (**F**) Trial 2 of cucumber at Lubbock, TX, USA. Different letters on the top of bars represent significant difference of means at $P \leq 0.05$. FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

control in both trials. In Trial 1, dry biomass of FHW, FH, FSW, PHW, PH, and PSW increased by 26%, 56%, 42%, 60%, 64%, and 42%, respectively compared with the control (Fig. 3A). In Trial 1, FH, PHW and PH had the highest plant dry biomass which were also comparable with FSW and PSW. FSW and PSW also had similar plant dry biomass, but FHW had significantly lower biomass than FH, PHW and PH, respectively. Among different biochar-compost combinations, hemp biochar-compost media (average of FH and PH) contributed the highest plant dry biomass followed by softwood-compost and then hardwood-compost media. Partial replacement of peat with biochar-compost (average of PHW, PH, and PSW) encouraged greater dry biomass than full replacement (average of FHW, FH, and FSW). Similarly, in Trial 2, 27%, 26%, 81%, 53%, 44%, and 79% dry biomass increases were observed in FHW, FH, FSW, PHW, PH, and PSW, respectively, compared with control (Fig. 3B). FSW and PSW had the highest plant dry biomass among all the treatments in Trial 2. Among different biochar-compost combinations, softwood biochar-compost media contributed the highest plant dry biomass followed by hardwood-compost and then hemp-compost media. Partial replacement of peat with biochar-compost encouraged greater dry biomass than full replacement.

The total number of fruits per plant was the highest in PHW and the lowest in control in both trials (Fig. 3C and D). In Trial 1, experimental substrates produced a greater number of fruits per plant, which ranged from 11% to 81% compared with the control (Fig. 3C). PHW produced significantly higher fruits per plant than other treatments. FSW had the second highest number of fruits/plant which was comparable with PSW, FHW and FH. Control shares similar lower number of fruits per plant with FHW and FH but significantly lower than FSW and PSW, respectively. Among different biochar-compost combinations, hardwood biochar-compost media contributed the highest number of fruits/plant followed by softwood-compost and then hemp-compost media. Partial replacement of peat with biochar-compost encouraged greater number of fruits/plant than full replacement. In Trial 2, the number of fruits/plant for alternative substrates ranged from 2% to 36% greater than the production from the control plants (Fig. 3D). PHW had the highest number of fruits per plant, which was comparable with FH and PSW. FH and PSW also had a comparable number of fruits per plant with control, FHW, and PSW. PHW, however, had significantly higher number of fruits/plant compared with control, FHW, FSW, and PH. Here, hardwood biochar-compost media contributed the highest number of fruits/plant than the other two biochar-compost combinations. Partial replacement of peat with biochar-compost encouraged greater number of fruits/plant than full replacement. Overall, this also shows that total number of fruits/plant were lower in Trial 2 compared with Trial 1.

The total fruit yield also showed a similar trend to the number of fruits per plant. PHW had the highest yield, and control had the lowest yield in both trials (Fig. 3E and F). In Trial 1, the total fruit yield was increased by 58%, 63%, 76%, 115%, 57%, and 84% in FHW, FH, FSW, PHW, PH, and PSW, respectively compared with the control (Fig. 3E). PHW had significantly higher fruit yield compared with all other treatments. FHW, FH, FSW, PH, and PSW share similar yield. Hardwood biochar-compost media contributed the highest yield followed by softwood-compost and least by hemp-compost media. Partial replacement of peat with biochar-compost yielded higher than full replacement. Similarly, in Trial 2, 8%, 17%, 1%, 38%, 1%, and 19% fruit yield increases were observed in FHW, FH, FSW, PHW, PH, and PSW, respectively compared with control (Fig. 3F). PHW yielded significantly higher than other treatments in Trial 2 also. The ranking follows same in Trial 1 for yields among biochar-compost combination like in Trial 1 with hardwood-compost combination with the greatest yield. Partial replacement had higher yield compared with full replacement treatments. However, the total yield was less in Trial 2 when compared with Trial 1.

Nutrient analysis of media, plant leaf, and fruits

Given the differences in pH among treatments (Table 3), nutrient availability might have varied across the media (Table 4), which subsequently altered the nutrient composition of plant leaves (Table 5) and fruits (Table 6). The soilless media elemental analyses showed differences in macronutrient (P, K, Ca, Mg, and S) and micronutrient (Fe, Mn, Cu, and Zn) concentrations among control and biochar-compost-amended treatments (Table 4). Control had the highest concentration of macronutrients such as K and Mg and the lowest concentration of P, Ca, and S compared with other treatments in both trials. In our experiment, P was significantly higher in FH and PH in Trial 1, and only in FH in Trial 2 compared with other treatments. Also, P was comparable among full and partial replacement of all three biochar types in Trial 1, but FHW and FH had significantly higher *P* value than PHW and PH in Trial 2, respectively. The control had a similar concentration of K with FSW in Trial 1, and FSW, PH, and PSW in Trial 2. Our results showed that K concentration was significantly higher in PH than FH in Trials 1 and 2, although the concentration was relatively higher in full replacement than in partial replacement for the other two types of biochar-compost treatments. For Mg, control treatment had similar concentration to FH, FSW, FHW, and PH treatments in Trial 1 and FSW, PH, PSW, and PHW treatments in Trial 2. A significant difference for Mg occurs in Trial 2 among

Table 4. Elemental composition (in ×1000 ppm) of different media at harvest in cucumber experiments at Lubbock, TX, USA.

	Media	P	K	Mg	Ca	S	Fe	Mn	Cu	Zn
Trial 1	Control	4.09 c[1]	28.90 a	27.03 a	10.20 f	1.08 f	30.84 a	0.34 c	0.07 ab	0.07 c
	FHW	4.27 c	21.58 cd	20.56 abc	34.01 b	2.20 d	19.77 cd	0.57 a	0.03 b	0.05 d
	FH	8.52 a	22.53 c	25.90 ab	38.73 a	3.65 a	23.44 bc	0.30 c	0.06 ab	0.11 a
	FSW	5.67 b	27.74 ab	23.75 abc	23.02 d	2.79 c	23.27 bc	0.46 b	0.07 ab	0.07 c
	PHW	3.52 c	19.53 d	18.72 c	29.37 c	1.63 e	18.82 d	0.61 a	0.11 a	0.05 d
	PH	7.54 a	26.08 b	26.73 a	29.97 c	3.11 b	25.38 b	0.31 c	0.09 ab	0.09 b
	PSW	5.70 b	26.12 b	19.29 c	18.72 e	2.32 d	23.96 bc	0.45 b	0.11 a	0.06 cd
Trial 2	Control	1.46 c	21.79 a	31.01 a	5.88 e	1.14 d	39.49 a	0.48 d	0.04 ab	0.07 d
	FHW	3.03 b	16.55 d	24.72 b	34.93 a	1.77 c	26.67 c	0.71 a	0.03 b	0.06 d
	FH	4.19 a	18.42 bcd	25.47 b	24.24 b	2.89 a	34.83 ab	0.49 d	0.05 a	0.11 a
	FSW	2.47 bc	20.59 ab	26.20 ab	16.13 cd	2.11 bc	38.39 ab	0.58 bc	0.05 a	0.08 b
	PHW	1.78 c	17.82 cd	27.02 ab	16.87 c	1.42 d	34.26 b	0.62 b	0.04 ab	0.07 d
	PH	2.50 bc	20.83 a	30.81 a	16.16 cd	2.15 b	37.77 ab	0.48 d	0.04 ab	0.08 bc
	PSW	2.38 bc	19.69 abc	28.15 a	13.04 d	1.77 c	36.02 ab	0.54 cd	0.04 ab	0.07 cd

[1] Different letters in a column indicate significant difference at $P \le 0.05$. FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

FH and PH; however, other full and partial replacement treatments remain comparable. In our experiment, Ca was found to be the mostly concentrated in FH and FHW in Trials 1 and 2, respectively. Among all the treatments, FH contained the highest S concentration in both trials. From our study, Ca and S concentration showed higher value in full replacement compared with partial replacement treatments. The micronutrient Fe was greater in the control treatments in both trials; however, FH, FSW, PH, and PSW had similar concentrations with the control in Trial 2. Our results showed that Cu did not vary much among the various treatments except FHW, which was the lowest in both trials. In our study, Mn and Zn showed an inverse relationship, meaning that when Mn was highly concentrated, Zn became scarce. From our study we found that Mn was the least and Zn was the highest in FH in Trial 1. In contrast, Mn was the highest and Zn was the lowest in PHW in Trial 1. A similar trend was observed in Trial 2, where Zn concentration was the greatest in FH, but it was the lowest in FHW, and Mn concentration was the greatest in FHW and it was the least in PH. The control also had lower concentrations for those two micronutrients in both trials.

The elemental analyses of cucumber leaf showed less variation in macro- and micronutrient concentrations among different media treatments (Table 5). Some variations in the concentration of macronutrients P, K, and S and micronutrients Fe, Mn, and Zn were observed among control and biochar-compost-amended media (Table 5). Elements such as P and S, which are essential macronutrients, were found at higher concentrations in control compared with biochar-compost-amended media treatments in both trials (Table 5). In our experiment, K remained unaffected across the treatments in Trial 1 but varied to some extent in Trial 2 with the greatest concentration in FHW. FHW had significantly higher value for K content than PHW. We found that Fe and Mn seem to be more concentrated in control; however, Zn concentration varied from the greatest in Trial 1 to the lowest in Trial 2. Also, Mn was significantly higher in PSW compared with FSW only in Trial 1. There was no significant difference among media treatments for Mg, Ca, and Cu in cucumber leaves in both trials.

The elemental analyses of cucumber fruit showed differences in all tested macro- and micronutrients concentrations among control and biochar-compost-amended media treatments (Table 6). The cucumber fruit of control treatment was found to be richest in elements P, S, Fe, Cu, and Zn in both trials (Table 6). A significant difference in P concentration occurs among FHW and PHW although, other full and partial replacement treatments remain comparable in both the trials. In our study, K concentration was significantly higher in FHW and FSW compared with PHW and PSW, respectively, only in Trial 2. It was found that Ca accumulation in fruits was greater in PHW in both trials. A significant difference occurs only among FHW and PHW in Trial 1 only for Ca concentration. We found that Mn concentration was similar among control, FSW, and PSW in Trial 1; however, there was a significant difference in Trial 2 having the highest concentration in control than other treatments. Our experiment showed that PHW had significantly higher Mn and Cu concentration compared with FHW in Trial 1 only. PHW and PSW had significantly higher concentration of Zn compared with FHW and PSW, respectively in Trial 2.

Discussion

Biochar-compost-amended media showed variations in chemical properties and nutrient concentrations, which elicited different responses in fruit yields and plant composition in both trials. The increase in EC with time likely resulted from daily fertigation. Regular fertigation causes nutrients and salt accumulation in the media in excess of plants uptake, which increases the EC of the media (Ludwig et al. 2013; van Iersel 1999). Cucumber is considered a salt-sensitive crop, and hence the increase in salinity can have a detrimental

Table 5. Elemental composition (in ×1000 ppm) of leaves collected across different treatments at harvest in cucumber experiments at Lubbock, TX, USA.

	Media	P	K	Mg	Ca	S	Fe	Mn	Cu	Zn
Trial 1	Control	24.01 a[1]	156.33 a	12.25 a	17.00 a	14.39 a	0.48 a	0.47 a	0.09 a	0.09 a
	FHW	14.82 c	139.77 a	13.72 a	22.55 a	11.84 ab	0.32 ab	0.25 b	0.03 a	0.07 b
	FH	15.85 bc	134.05 a	14.16 a	18.27 a	12.89 ab	0.30 b	0.18 b	0.04 a	0.07 b
	FSW	15.68 bc	101.57 a	12.92 a	24.89 a	11.26 ab	0.30 b	0.30 b	0.02 a	0.07 b
	PHW	17.74 bc	142.81 a	12.33 a	23.15 a	12.16 ab	0.35 ab	0.29 b	0.04 a	0.07 b
	PH	20.32 ab	128.86 a	15.48 a	21.92 a	13.46 ab	0.35 ab	0.23 b	0.04 a	0.07 b
	PSW	20.66 ab	137.66 a	12.48 a	26.67 a	9.87 b	0.39 ab	0.48 a	0.04 a	0.06 b
Trial 2	Control	22.17 a	72.24 ab	12.3 a	11.45 a	7.30 a	2.05 a	1.00 a	0.01 a	0.04 b
	FHW	9.12 b	87.746 a	9.2 a	11.95 a	6.54 a	0.25 b	0.18 b	0.01 a	0.04 b
	FH	9.27 b	77.35 ab	12.28 a	20.70 a	7.06 a	0.34 b	0.23 b	0.01 a	0.05 b
	FSW	11.10 b	79.89 ab	11.37 a	23.12 a	7.07 a	0.52 b	0.32 b	0.01 a	0.05 b
	PHW	10.81 b	63.10 b	11.34 a	26.31 a	7.65 a	0.66 ab	0.47 b	0.01 a	0.04 b
	PH	10.20 b	70.83 ab	10.81 a	25.43 a	8.08 a	1.16 ab	0.48 b	0.01 a	0.06 a
	PSW	12.23 b	83.96 ab	8.78 a	12.48 a	6.68 a	0.28 b	0.30 b	0.03 a	0.06 a

[1] Different letters in a column indicate significant difference at $P \le 0.05$. FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

Table 6. Elemental composition (in ×1000 ppm) of fruits collected across different treatments at harvest in cucumber experiments at Lubbock, TX, USA.

	Media	P	K	Ca	S	Fe	Mn	Cu	Zn
Trial 1	Control	93.47 a[1]	64.60 c	1.43 b	4.12 a	0.13 a	0.04 ab	0.01 a	0.05 a
	FHW	6.50 c	75.11 ab	1.72 b	3.50 ab	0.08 b	0.03 b	0.01 b	0.033 c
	FH	7.23 bc	72.75 abc	2.13 ab	3.79 ab	0.08 b	0.03 b	0.01 b	0.04 bc
	FSW	7.83 b	78.28 ab	2.66 ab	4.04 a	0.09 b	0.04 ab	0.01 b	0.04 b
	PHW	7.93 b	79.01 a	3.31 a	4.13 a	0.09 b	0.05 a	0.01 a	0.03 bc
	PH	6.83 bc	68.45 bc	1.39 b	3.34 b	0.09 b	0.03 b	0.01 b	0.030 bc
	PSW	7.93 b	69.86 abc	2.26 ab	3.97 ab	0.09 b	0.04 ab	0.01 ab	0.04 b
Trial 2	Control	10.77 a	55.15 d	0.84 ab	3.75 a	0.12 a	0.05 a	0.01 a	0.05 a
	FHW	6.29 c	66.03 ab	0.89 ab	3.07 bc	0.06 b	0.02 b	0.01 b	0.02 e
	FH	6.20 c	65.81 abc	0.64 b	2.82 c	0.06 b	0.02 b	0.01 b	0.03 cd
	FSW	6.92 bc	70.07 a	0.98 ab	3.22 b	0.06 b	0.03 b	0.01 b	0.03 d
	PHW	7.15 b	60.84 c	1.02 a	3.22 b	0.06 b	0.02 b	0.01 b	0.04 bc
	PH	6.81 bc	63.76 bc	0.64 b	3.12 bc	0.06 b	0.02 b	0.01 b	0.04 bc
	PSW	7.38 b	62.78 bc	0.91 ab	3.27 b	0.07 b	0.02 b	0.01 b	0.04 b

[1] Different letters in a column indicate significant difference at $P \leq 0.05$. FH = full hemp; FHW = full hardwood; FSW = full softwood; PH = partial hemp; PHW = partial hardwood; PSW = partial softwood.

effect on the crops (Stanghellini et al. 2019). Biochar has also been reported to increase EC of the substrate due to its alkaline nature, larger surface area, and charge density (Fan et al. 2015). This may be the reason why the basic nature of the biochar-amended media maintained higher EC compared with control (Table 2). High EC of biochar is generally attributed to high ash content in biochar. The decreased pH with time from basic to neutral or even in slightly acidic range in biochar-compost-amended media (Table 3) can be attributed to application of acidic fertilizer (Potential acidity 251.7 kg calcium carbonate equivalent per ton). This result was similar to findings of Huang et al. (2020), who reported that the pH of compost-biochar media reduced with time due to the acidifying nature of fertilization. Generally, many of the biochars have a neutral to basic pH, making them a suitable liming material that helps to increase the pH of the substrate (Huang and Gu 2019). The negative charge of biochar helps to avoid peat acidity in the soilless substrate (Blok et al. 2017). It has been well established in literature that the pH of soil/media could play an important role in availability of nutrients to plants, which could, in turn, have an impact on plant growth. A pH value ranging between 5.5 and 7.5 is usually considered ideal for growth of most plants, and this pH range has been achieved in biochar-compost-amended treatments in current study with the exception of the control. This might be the reason for better nutrient availability and better plant growth in biochar-compost-amended treatments compared with control.

Plant height was significantly lower in control compared with biochar-amended media treatments (Fig. 1). One potential reason for the decrease in height of control plants could be poor plant nutrient availability due to unfavorable pH and EC of control media (Table 4). The control medium pH was beyond the nutrient availability pH range for most of the essential nutrients, which may have hampered the growth of the plants. The acidic media in control did not favor plant growth, it may be due to reduced uptake of nitrogen (N) and hence height was reduced. Although we did not measure nitrogen in our study, the study by De Lucia et al. (2013) reported that when peat-based substrate with no compost was used in the media, it lowered the pH of the media and reduced N availability. In our study, the control treatment may have been deprived of N and led to lower growth compared with other compost-biochar treatments. Our study is in line with Jahromi et al. (2012), who reported that the lowest pH was associated with the lowest tomato (*Solanum lycopersicum*) and cucumber seedling height. This implies that pH can greatly affect the height of plants via nutrient deficiency, such as N deficiency. The reduced height could also be due to low pH, which suggests a lower nutrient concentration of P, Ca, and S in the control (pH $<$5.0). The height of cucumber plants in all treatments in Trial 2 was considerably lower than in Trial 1. This could be because of a severe pest infestation during the Trial 2 period, which likely affected overall plant growth.

Chlorophyll content was significantly lower in control compared with other treatments up to 38 DAP, but it was the highest in control at 52 DAP in Trial 1 (Fig. 2A). A similar pattern was also observed in Trial 2 (Fig. 2B), in which the control had the highest chlorophyll content at 52 DAP. A previous study showed that nutrient dynamics, especially K, Fe, and Mn in leaves are positively correlated to the chlorophyll content (Bu et al. 2022). In our study, all three elements were significantly higher in control plant leaves (Table 5), which might have helped to accumulate greater chlorophyll content in control plants compared with other treatments toward the end of both experiments. At the end of both trials, it was observed that FH and FHW had the lowest chlorophyll content compared with other treatments. This can also be attributed to the elemental composition of K, Fe, and Mn in leaves. Although K accumulation did not show a significant difference in FH and FHW compared with control, the micronutrients Fe and Mn drastically lower in leaves of FH and FHW in both trials (Table 5), which may have contributed to low chlorophyll content. Another reason for the lower chlorophyll content in all the biochar-compost-amended treatments could be attributed to higher EC. Tiwari et al. (2021) and Heidari (2012) have reported the negative effect of salinity (high EC) on chlorophyll content in the salt-sensitive crops. The reason for the loss of chlorophyll in relatively higher salinity is due to photo inhibition or formation of reactive oxygen species (ROS) (Heidari 2012; Kato and Shimizu 1985). The *Pn* was significantly higher in control compared with other media treatments at 11 and 52 DAP in Trial 1 (Fig. 2C) and at 45 DAP in Trial 2 (Fig. 2B). The decrease in *Pn* in the all biochar-compost-amended treatments in both trials was due to decrease in chlorophyll content. This statement can be supported by the finding of Heidari (2012) that reduction of photosynthesis was due to reduction in chlorophyll content in salt-sensitive crop such as basil (*Ocimum basilicum*) grown under high salinity (high EC). Our finding is consistent with the results of Seehausen et al. (2017), who reported a strong positive relationship between chlorophyll content and *Pn* in *Abutilon theophrasti*, while comparing between biochar-amended, compost-amended, and biochar-compost-amended standard peat media. Our results show a different trend from their findings because their experiment reported a significant increase in *Pn* in biochar-compost-amended treatment compared with standard (peat–perlite–vermiculite) media, which contrasts with our results. This may be because in our study, the cucumbers were under salt stress (high EC), whereas they did not have any salt stress on the plants. For a salt-sensitive crop like cucumber, elevated salt stress levels ($>$2 dS/m) in the biochar-compost media may have shown lower chlorophyll content and Pn. In the same study by Seehausen et al. (2017), there was no significant difference in *Pn* among treatments when tested for *Salix purpurea.* This indicates that the response of *Pn* drastically varies among species. In our case, the control plants may have had better CO_2 absorption than other treatment plants. The chlorophyll content and *Pn* were lower in Trial 2 compared with Trial 1, which might be attributed to leaf damage caused by pests during Trial 2.

Plant dry biomass, number of fruits per plant, and fruit yield were significantly higher in biochar-amended treatments compared with the control in both trials (Fig. 2A–F). The greater plant biomass in all the treatment except control was due to increased growth, which was evidenced by greater plant height (Fig. 1). These results are supported by a study, where plant height of *Abutilon theophrasti* was drastically increased and caused higher dry biomass accumulation in peat amended with biochar or compost individually or in combination compared with standard peat media (Seehausen et al. 2017). Dry biomass reduction in the control compared with other biochar-compost-amended treatments can also be related to chlorophyll content which is an indicator of plant N status (Liu et al. 2006). The chlorophyll content remained lower in the control compared with other treatments for most of the growing season. This indicates there could have been inadequate N in the control plants, which could have reduced plant growth and ultimately plant biomass. Although chlorophyll content considerably increased in the control toward the end of the growing season, it was likely too late to contribute to the growth of cucumber plants. According to Zhang et al. (2014) and Zulfiqar et al. (2019), when biochar and compost mixture was added to a potting substrate, it enhanced plant N which ultimately enhanced plant growth and plant biomass. The drastic reduction in fruit number per plant was observed in control in both trials. It could be due to lower biomass in control plants. Kõlõc et al. (2018) revealed that an increase in plant biomass can increase fruit number in tomato while growing in soilless media. The enhanced fruit yield in biochar-compost-amended plants was attributed to vigorous growth, sustained physiological parameters, and greater dry biomass and fruit number. Medyńska-Juraszek and Ćwieląg-Piasecka (2021) reported that when biochar is used as a growing media component, it can increase growth and yield of vegetables like cucumber because of higher retention capacity of nutrients and water. According to Huang et al. (2019), a mixture of biochar (60% to 80%) and compost (5%) (v/v) enhanced the yield of tomatoes in a peat-based substrate medium by improving the hydro-physical property of the media and increasing growth index and dry weight of stem and root biomass of the plant. Another study on bell pepper (*Capsicum annuum*) by Liu et al. (2019) revealed that hardwood biochar at 70% and vermicompost at 30% (v/v) yielded more compared with higher rates of biochar due to higher leaf area, growth index, and dry weight of vegetative biomass in bell pepper. Additionally, Ain-Najwa et al. (2014) claimed that peat amended with biochar can result in a high yield due to bigger stem diameter and greater fruit number, along with maintaining postharvest quality due to improvement in fruit color development in cherry tomatoes. The addition of compost along with biochar ameliorates the media. The cotton burr-compost added in biochar-amended media might have contributed to greater yield through the slow release of essential nutrients such as N, P, and K (Gruda 2019). Biochar generally contains ∼1% of nitrogen (Gruda 2019), which is why it needs to be combined with other sources of nutrients such as compost for proper growth of plants. The slow release of nutrients from compost meets the demand for the nutrients of the growing crop for vegetative growth and, ultimately, yield (Rogers 2017). This statement can also be supported by the results of Vandecasteele et al. (2018), who found that compost can act as a source of essential nutrients in the growing media for strawberry (*Fragaria ×ananassa*) production. In our experiment, partial replacement of all the biochar types (except hemp biochar) resulted in greater yield than complete replacement although significant increase in yield was only obtained in for hardwood biochar (FHW vs. PHW). Our result is in line with observations by Allaire and Lange (2017, 2018), who compared partial replacement of pH adjusted peat with three types of biochar at 13%, 26%, and 40% rate and found that application rate of 25% biochar (or 40% replacement) can provide better results in ornamental plant white spruce (*Picea glauca*). This could be due to the negative effects of greater relative amounts of biochar in soilless media, as similarly reported by Regmi et al. (2022) and Zulfiqar et al. (2019). In the current study, fruit yield was significantly higher in partial replacement of peat with hardwood biochar-compost mixture compared with full replacement of peat in both trials. In Trial 2, there was an increase in fruit yield for PSW but decrease in PH compared with FSW and FH, respectively. The yield of cucumber 'Piccolino' obtained by Yang et al. (2023) and grown in a Dutch bucket system with similar substrate media was higher than the yield obtained in our experiment, which could be due to different growing environments and management practices. Also, the plants in our experiment were grown under excessive fertigation, which might have stressed the plants due to high salinity (high EC). However, Bhat et al. (2013) reported $<$1-kg yield for the same cultivar growing under a similar substrate combination. This indicates that the yield of cucumber can vary based on the growing condition and practice. The dry biomass and fruit yield in Trial 2 were reduced compared with Trial 1 due to the severe spider mite and aphid infestations during Trial 2. van Lenteren (2007) recognized whitefly and spider mites to be the major economic pest attacks in greenhouse cucumber. In our experiment, there was a trend in fruit number per plant to increase in biochar-compost inclusion treatments compared with the control. The higher number of fruits per plant can be another reason for higher yield in biochar-compost-amended treatments. In these experiments, the relationship between number of fruits/plant and fruit yield was stronger ($R^2 = 0.81$) compared with relationship of dry biomass and fruit yield ($R^2 = 0.37$) (Supplemental Fig. 1). Heuvelink (1997) also reported that the fruit yield is largely determined by number of fruits in tomato. A similar strong relationship was obtained by Zhang et al. (2011) in greenhouse cucumber, where authors observed a linear increase in fruit yield ($R^2 = 0.78$) with each increase of fruit number ($R^2 = 0.84$) when irrigation water level was increased.

There was nutritional variability due to inclusion of biochar-compost mixture in the standard peat substrate (Table 4). Zulfiqar et al. (2019) suggested that the chemical properties of peat substrate can be affected by inclusion of biochar or compost or in combination. Nutrients tend to be available in their normal pH range in media. However, some element accumulation was highly unanticipated. For example, Mg concentration was the highest in the control treatment which had the lowest pH (Table 4), although the literature suggests that Mg availability is higher around neutral pH (Alam et al. 1999). Due to fertilization, the smaller plants in control did not take up as much Mg as the other taller plants with higher biomass. The plant sizes of the control treatment were small hence the concentration tended to be higher because of the regular fertigation compared with other bigger plants in other media (Fig. 1). The lower K value in biochar-amended media (Table 4) suggests that K was either leached from biochar (Angst and Sohi 2013; Regmi et al. 2022) or may have been taken up by plants. The concentration of some macro nutrients P, K, Ca, and S in different medias were lower in Trial 2 compared with Trial 1 except Mg. This could be due to the difference in pH and EC value between Trials 1 and 2 when the samples were analyzed. The lower concentration of P and S in all media treatments (Table 4), and higher concentration of these elements in leaves (Table 5) and fruit (Table 6) imply that nutrients have been taken up by cucumber plants. The literature suggests that higher concentration of K establishes an antagonistic effect with Mg and Ca, which was not evident in our leaf samples, similar to the findings of Regmi et al. (2023) who tested biochar levels in the violas plant *Viola cornuta*). The highest P concentration in leaves of control plants contradicts the results of Zulfiqar et al. (2021), where leaf P concentration in peat–perlite substrate was the lowest. This can be attributed to a difference in the proportion of peat and perlite between these studies. Elements such as P, Fe, Mn, and Zn were significantly lower in leaves of biochar-amended plants compared with control plants (Table 5). These elements tend to be available in a slightly acidic to neutral pH range; however, pH in biochar-compost treatments had a higher pH range for most of the time. Similar results were reported by Regmi et al. (2022), who found that these elements were comparatively lower in biochar-amended Viola plants compared with peat substrate. The concentration of some macro nutrients P, K, Mg, and S in plant tissues of different medias were lower in Trial 2 compared with Trial 1. This could also be due to the difference in pH and EC value between Trial 1 and Trial 2 at the time when the samples were analyzed. The cucumber fruits of control treatment were found to be the richest in elements such as P, S, Fe, Cu, and Zn (Table 6). These elements, which were available in control media treatment, may have been accumulated in the fruits. K concentration significantly dropped in fruits of control media. This may be because K in the media has been majorly translocated toward leaves. Most of the micronutrient were at higher concentrations in fruits of the control group compared with other treatments. The micronutrients which becomes available in low pH range are found to be accumulated in fruits of the control treatments which had comparatively low pH than other treatments.

Conclusion

This study was focused on determining the efficacy of different biochar-compost mixtures as a sustainable means for replacing peat either partially or completely in substrate container cultivation of cucumbers. All biochar-compost-amended treatments showed higher plant height, plant dry biomass, number of fruits, and fruit yields compared with the control plants. The inclusion of a biochar-compost combination in standard peat substrate can bring variation in the nutritional status of the media, which contributes to supplying essential elements to plant leaves and fruits. The control treatment fruits and leaves had higher concentrations of macronutrients such as K and Mg and lower concentrations of P, Ca, and S compared with other treatments in both trials. Micronutrients such as Fe, Mn, Cu, and Zn were found in comparatively greater concentration in control treatment leaves and fruit than compost-biochar-amended treatment because these elements become available at low pH ranges, which was characteristic of the control treatment. In general, partial replacement of peat with biochar and compost appeared to produce better results compared with complete replacement of peat except hemp biochar. For profitable and environment-friendly soilless substrate, more research is needed to replace peat with different biochars especially those produced from locally available feedstock.

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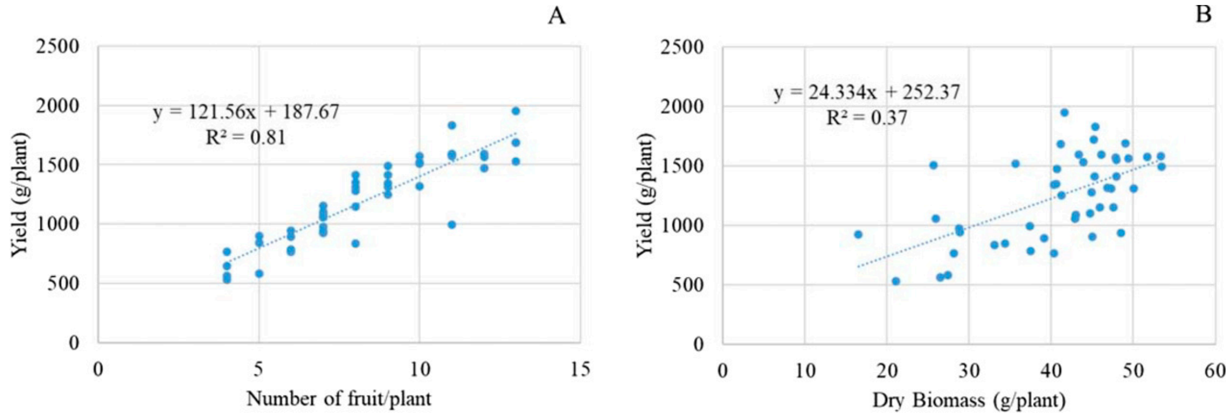

Supplemental Fig. 1. Correlation between (**A**) number of fruits/plant and yield and (**B**) dry vegetative biomass and yield.