

Article

Poultry Litter Biochar Increases Mycorrhizal Colonisation, Soil Fertility and Cucumber Yield in a Fertigation System on Sandy Soil

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Abstract: There is a continuing argument about the benefits of biochar on arbuscular mycorrhizal (AM) symbiosis, crop growth, yield, and fertility of soil. There is also limited research on the effects of biochar on AM colonization, cucumber yield, and soil fertility improvement. Therefore, this investigation aimed to determine the impact of poultry litter biochar (PLB) on colonization of roots by indigenous AM fungi in agricultural soil and their contribution to cucumber yield, nutrition, and soil fertility improvement. A field trial was conducted to assess the effect of PLB combined with compound poultry manure (CPM) and nitrophos (NP) fertilizer to investigate the response of treatments on nutrient-deficient sandy soils. Plant growth responses to biochar showed better plant growth and yield of cucumber. Application of biochar with and without CPM and NP reduced the negative impact of nutrient deficiency stress on cucumber growth. AM fungal colonization, soil fertility, and cucumber yield were improved with the combined application of biochar, CPM, and NP fertilizer. Post-harvest, soil C, N, P, K, Ca, Mg, S, Zn, Cu, Fe, and Mn increased with application of biochar applied with CPM and NP. Biochar application with CPM and NP also increased the percent root colonization of cucumber. Use of biochar with CPM and NP has the potential to improve plant growth, yield, nutrient uptake, and soil fertility. Further studies in various agro-ecological conditions would help utilize this technology in sustainable crop production.

Keywords: arbuscular mycorrhizal fungi; cucumber; poultry litter; manures; biochar; plant growth; nutrients uptake

1. Introduction

Increase in atmospheric CO₂, CH₄, and other greenhouse gases is causing climate change, leading to global warming and related concerns. The sequestration of carbon (C) in soil is receiving more attention as a means to combat climate change. With the discovery of so-called Terra Preta, an extremely fertile soil enriched with carbonised biomass in Amazonia [1,2], biochar has appeared as a possible solution for sequestration of C in soil [3].

Biochars are products of the pyrolysis process, an irreversible thermochemical conversion of biomass from either plant or animal origins heated at very high temperature (≥250 °C) in a nil or limited oxygen environment [4,5]. Biochar properties such as pH, specific surface area, pore volume, cation exchange capacity (CEC), other nutrients, volatile matter, ash, and carbon content are mostly

dependent on the nature and source of feedstock used for its production, temperature, and activation treatments for pyrolysis [5–9]. For example, biochar produced at a high pyrolysis temperature has high specific surface area, porosity, pH, and ash and carbon contents, but has low values of CEC and volatile matter [5,10]. Different feedstocks produce biochar with variable characteristics due to their variation in lignin, cellulose, and moisture content. Animal litter and solid waste biochars have a lower surface area, carbon content, and volatile matter, but higher CEC, compared to crop residue and wood biomass biochar.

Application of biochar to soil is testified to have the potential to increase soil fertility and consequently agricultural productivity [6,11], and enhance nutrient content, nutrient use efficiency, and water holding capacities of soil [12]. It also influences soil hydraulic properties [13] and reduces emissions of N₂O [14], and can improve soil quality and crop production for less fertile soil more than fertile soil [15]. However, some studies have reported that biochar addition to soils can have no effect or a negative effect on soil properties and biomass growth [15]. Many researchers have stated that the use of charcoal amendments in tropical regions can enhance and maintain fertility and productivity of soils [11,16]. The most essential and helpful effects of biochar are improvement in physical, chemical, and biological characteristics of soils [17], and an increase in the cation exchange capacity of soil [18,19]. It also improves C, N, and P retention in soils due to larger surface area [20], better microbial activities [21], and increased arbuscular mycorrhizal (AM) fungal colonization [22].

Biochar is receiving attention as a stable soil amendment because it contains stable forms of C which are expected to stay inside soil for many years [23–25]. Biochar also contains variable concentrations of nutrients, including phosphorus (P) and nitrogen (N) [6,7]. Addition to soil of biochar alone or in a mixture of biochar and compost significantly increases the aboveground shoot biomass and belowground root biomass of plants, and the P and K concentration of biomass [26]. However, soil types, different biochar feedstocks, and fertilization play essential roles in the growth and biomass of plants [10].

Application of biochar to soils either increases or decreases the colonization of roots by AM fungi based on the concentration of P and N in biochar [22,27–30]. There are many unwanted compounds in biochar, such as crystalline silica, phenolic compounds, dioxin, and volatile compounds, depending on the source of biochar [31,32], and these can also influence AM fungal colonization. Variability in the quality of biochar has different effects on AM colonization, and have the potential to affect P uptake and growth of plants to varying degrees [29,33]. Therefore, biochar application has shown increased plant growth and yield [6], and affects the involvement of AM fungi in a range of possible mechanisms [22,34]. Several studies have also reported an increase in AM colonization with biochar application [27,30,35,36] because biochar can enhance microbial activity in soil, including of AM fungi, by providing a favorable habitat [34,36,37]. Extraradical hyphae of AM fungi extend inside the fragments of biochar in soil [38] and increase P uptake by plants [39,40]. However, despite the demonstrated impacts of biochar on root colonization by AM fungi, the relative influences of biochar applied with inorganic and organic fertilizers on AM fungal colonization are still largely unknown. Potential interactions between biochar and plant parameters, including colonization of roots by AM fungi, can occur both directly and indirectly. Direct interactions can result from an effect of biochar on growth of hyphae before root colonization [30], whereas indirect interactions can occur if biochar influences root growth, which leads to a change in root colonization [27,30,35]. Biochar can alter root colonization by stimulating the growth of hyphae in soil before establishment of mycorrhizas under water-limiting conditions [9].

Gorovtsov et al. [41] reported various effects of biochar on soil microorganisms, although the actual mechanisms of their interactions are not yet clear. Paymaneh et al. [13] suggested that addition of aged softwood biochar to acidic or alkaline agricultural soils affected the growth of grass, and its nutrient uptake depending on soil types, but did not affect composition of root-borne arbuscular mycorrhizal fungi. Meta-analysis showed that biochar application has significant effects on soil microbial growth, particularly soil fungi and Gram-positive bacteria [42]. The effect of biochar depends on biochar

feedstocks, application rate, weathering and aging of biochar [43], and interactions of biochar in soil minerals, soil types, etc. [13].

Poultry litter has a high nutrient content. Therefore, it can be used as organic fertilizer for soil amendment [44]. However, a high rate of application and its direct use in soil have caused many environmental problems, such as ammonia volatilization, nitrogen mineralization, water contamination, greenhouse gas emission, and odor [45]. Therefore, production of poultry litter biochar has a high potential for use as an organic fertilizer in soil improvement [44], thus increasing seed germination, water-holding capacity, pH, and nutrient contents of soil at a low application rate [6,46].

Therefore, an investigation was conducted to elucidate the effect of biochar with different combinations of nutrient amendments in a field study using a P-deficient soil sown with cucumber. Arbuscular mycorrhizal colonization, plant growth, cucumber yield, and nutrition of cucumber plants were assessed. The goal was to determine the influence of biochar effects on plant growth and some aspects of soil fertility with interactions between biochar, fertilizers, and indigenous AM fungi in soil. It was expected that poultry litter biochar (PLB) would influence plant growth and that this would be due to higher nutrient concentrations in biochar (N, P, and K), which may become more available to plants after biochar amendment of soils.

2. Materials and Methods

2.1. Biochar

Biochar used was produced from poultry manure under a temperature of 450 °C and sieved to 2 mm (Table 1). The pH of biochar measured in water and 0.01 M CaCl₂ at a 1:5 (w/v) ratio was 9.0 and 8.5, respectively, following the method of Rayment and Lyons [47]. The water-holding capacity of biochar was measured using a gravimetric method [48]. A composite sample of biochar was used to determine total C and N content by using the dry combustion method (Vario MACRO CNS; Elementar, Germany). Total P in biochar was measured after the digestion of biochar in 3:1 HNO₃-HClO₄ and then P was measured in solution using the molybdenum-blue method on a spectrophotometer [49]. Soil available P, microbial biomass P, and organic P in soil were extracted after plant harvesting [50,51] and measured using the above-mentioned method.

Table 1. Properties of biochar made from poultry litter feedstock used in this experiment. Note: EC, electrical conductivity; CN ratio, carbon nitrogen ratio.

Properties	Units	Concentration
pH (CaCl ₂)	—	9.0
EC	mS cm ⁻¹	7.7
Total C	%	38.8
Total N	%	3.7
CN ratio	—	10.57
Water holding capacity	%	70
Phosphorus (P)	%	2.53
Potassium (K)	%	2.08
Calcium (Ca)	%	4.5
Magnesium (Mg)	%	1.03
Sodium (Na)	%	1.07
Sulphur (S)	%	0.46
Copper (Cu)	mg kg ⁻¹	271.4
Iron (Fe)	mg kg ⁻¹	6494.6
Manganese (Mn)	mg kg ⁻¹	1016.7
Zinc (Zn)	mg kg ⁻¹	1007.5
Arsenic (As)	mg kg ⁻¹	6.4
Cadmium (Cd)	mg kg ⁻¹	<0.5
Lead (Pb)	mg kg ⁻¹	20.3
Chromium (Cr)	mg kg ⁻¹	26.9

2.2. Site Description

Soil (0–10 cm) used in the experiment was collected from a cucumber trial site at Geraldton, Western Australia (latitude 29°19', longitude 115°44') for analysis before and after the trial. Geraldton has a Mediterranean climate with a mean annual rainfall and temperature of 400 mm and 19.7 °C, respectively. The soil was classified as Tenosol (sand over gravel) [52] and humic Dystrocherepts [53] with 92% sand, 5% silt, and 3% clay particles. Before the start of the experiment, soil was analyzed for some basic properties, including soil pH of 4.8 measured in 0.01 M CaCl₂ at 1:5 (w/v) ratio and soil organic matter of 10.2 g kg⁻¹ measured using the dry combustion method. Soil contained 0.5 g kg⁻¹ total N, and 6 and 4 mg kg⁻¹ NO₃-N and NH₄-N, respectively. This soil was selected for its sandy texture, which was deficient in available P (7.3 mg kg⁻¹) and was appropriate for a mycorrhizal response study.

2.3. Experimental Design

Cucumber (*Cucumis sativus* L.) was grown for 160 days under field conditions in an agricultural soil at Geraldton, Western Australia following amendment with compound poultry manure (CPM), containing N, P, K at a ratio of 5.4:1.0:2.7, and derived PLB in combination with or without nitrophos (NP) fertilizer including a no biochar added control. There were six treatments with one control applied in a randomized complete block design (RCBD) with three replicates. Details of treatments used are presented in Table 2. Biochar was applied in a field using a mini-spreader (Figure 1a,b).

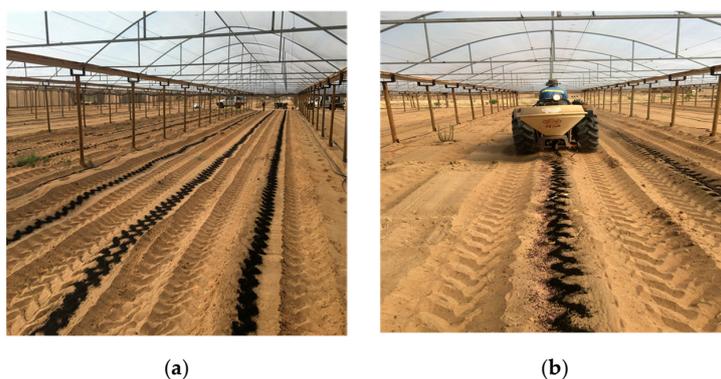


Figure 1. Application of biochar and other amendments (a) in rows and (b) mini-spreader used.

Table 2. Treatment composition applied to the cucumber field.

Treatment	CPM	NP	PLB
	t/ha		
Control	9	5	0
Treatment 1	9	5	7
Treatment 2	9	5	13
Treatment 3	0	0	13
Treatment 4	1	2	7
Treatment 5	1	2	13
Treatment 6	0	0	33

CPM = compound poultry manure, NP = nitrophos, PLB = poultry litter biochar.

2.4. Sampling and Analyses of Soil and Plant

At harvest, cucumber leaves were randomly collected from each plant and dried at 60 °C for at least 72 h to determine leaves' dry weights (DW). Oven-dried leaves were ground, digested in 3:1 ratio of HNO₃-HClO₄ and analyzed for various nutrient analysis [54]. The P concentrations in digest were measured by molybdenum-blue method [49].

2.5. Assessment of Arbuscular Mycorrhizal Fungi Colonization

After harvesting the crop, root samples (0.5 g) were washed using tap water, cut into 1 cm pieces, and cleared in 10% KOH solution. Then, root samples were acidified and stained with 0.05% trypan blue in lactoglycerol and destained in lactoglycerol [55,56]. Percent root length colonization (%) and root length colonized (m pot⁻¹) were measured using a gridline intercept method under a microscope at 100× magnification [57,58].

2.6. Statistical Analyses

Analysis of variance was undertaken using Genstat (v.18) (VSN International, Hemel Hempstead, UK). One way analysis of variance was used to observe any significant impact of treatments on soil and plant parameters. A least significant difference (LSD) was applied to test any significance between the means at $p \leq 0.05$.

3. Results

3.1. Characteristics of Poultry Litter Biochar

The pH and EC of biochar were 9.0 and 7.7 mS cm⁻¹, respectively, whereas, the water-holding capacity of biochar was 70%. Total C and N concentration was 38.8% and 3.7% with a C to N ratio of 10.57. Total P, K, Ca, Mg, Na, and S levels in PLB were 2.53, 2.08, 4.5, 1.03, 1.07, and 0.46%, respectively, which indicates the presence of a significant amount of nutrients in biochar. The concentrations of micronutrients (Cu, Fe, Mn, and Zn) and some heavy metals (As, Cd, Pb, and Cr) were also found to be at appropriate and safe ranges for plants and soil (Table 1).

3.2. Biochar Effects on Plant Growth, Yield and Nutrition

Cucumber growth and yield responded to different treatments, either positively or negatively, depending on concentration of nutrients present in different applied treatments ($p \leq 0.05$; Figures 2 and 3). Data regarding cucumber leaf biomass statistically increased in trend T6 > T4 > T2 and these closely resembled the effect of T1, whereas the effect of T3 and T5 was more than that of the control but not significantly different (Figure 2). Comparison of applied treatments showed that application of T2 and T4 significantly enhanced cucumber yield, whereas the effect of T5 was positive initially and then decreased the yield. The impact of all other remaining treatments, including T3, T1, and T6, was negative on cucumber growth and yield (Figure 3).

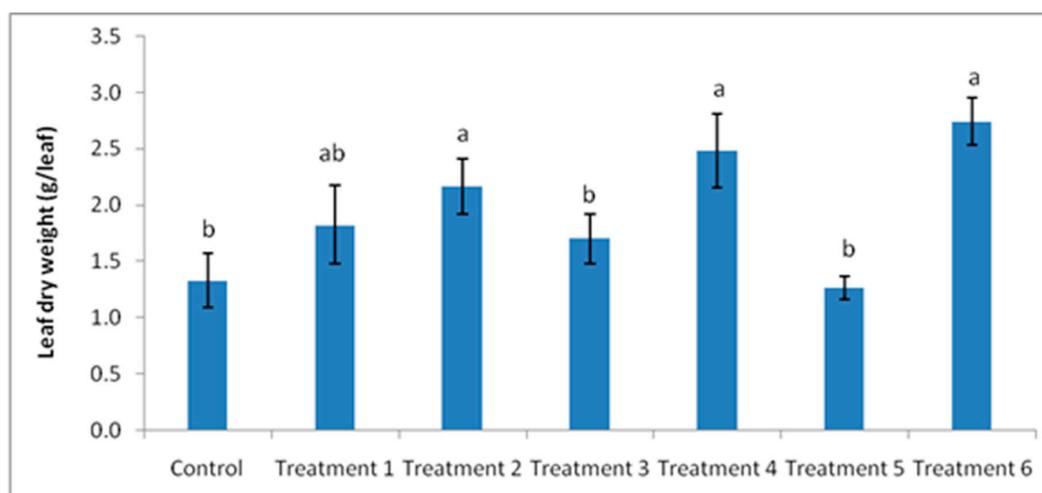


Figure 2. Effect of biochar, fertilizer, and manure on leaf biomass of cucumber. Different letters above the bars suggested that these values are significantly different at $p \leq 0.05$.

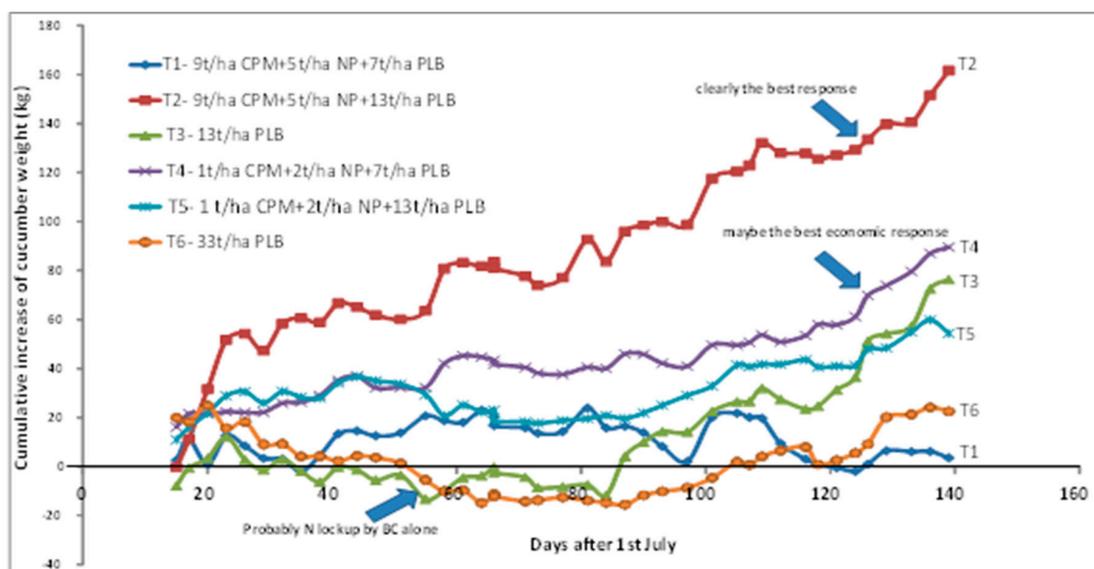


Figure 3. Effect of biochar, fertilizer, and manure on cumulative cucumber yield over control (CPM = compound poultry manure, NP = nitrophos, PLB = poultry litter biochar).

The nutrient concentrations in cucumber leaves were influenced by different treatments (Table 3). This indicates that application of biochar with and without poultry manure and chemical fertilizer reduced the negative impact of both macro- and micronutrient deficiency stress on cucumber growth and nutrient content of leaves, which were grown on nutrient-deficient sandy soil. Maximum N, P, and K concentration in cucumber leaves were found in plots treated with T3, which were not significantly different from other treatments; however, in comparison with T6, all treatments showed increased nutrient concentrations. The concentrations of secondary macronutrients such as S and Mg were not significantly affected by different treatments. However, Ca was substantially affected by treatments with a maximum Ca concentration of 5.2% in T2 and minimum of 3.3% in T5 (Table 3). The concentration of micronutrients in soil showed variable effects of increases and decreases with application of PLB alone and in combined with CPM and fertilizers compared with the control.

Table 3. Effect of poultry litter manure, biochar, and conventional fertilizers on nutrient concentrations in cucumber leaves.

Treatment	N	P	K	S	Ca	Mg	Zn	Cu	Fe	Mn
	%	%	%	%	%	%	mg kg ⁻¹			
Control	4.0	0.5	2.5	1.0	4.2	0.9	285	15.5	206	336
Treatment 1	4.1	0.5	2.5	1.0	5.0	1.1	380	19.1	345	478
Treatment 2	4.4	0.5	2.5	1.1	5.2	1.0	385	17.6	365	502
Treatment 3	4.7	0.6	2.6	0.9	4.4	1.0	365	15.5	251	455
Treatment 4	4.2	0.5	1.4	1.0	3.7	0.7	405	24.3	329	539
Treatment 5	4.9	0.7	2.6	0.8	3.3	0.8	382	25.8	209	348
Treatment 6	3.2	0.3	1.2	0.8	3.5	0.7	346	14.7	1013	362
LSD $p < 0.05$	0.8	0.2	1.0	Ns	1.0	ns	81	5.3	121	102

3.3. Biochar Effects on Mycorrhizal Fungi Colonization

The mycorrhizal fungi colonization of roots (assessed as % length of root colonized) was affected by compound poultry manure, fertilizers, and biochar as shown in Figure 4. Biochar addition had variable effects on % root colonization when added with and without CPM and chemical fertilizers.

The highest mycorrhizal fungi root colonization (%) was observed for T4, followed by T5 and T6. The lowest mycorrhizal colonization (%) was observed in all other treatments, including the control.

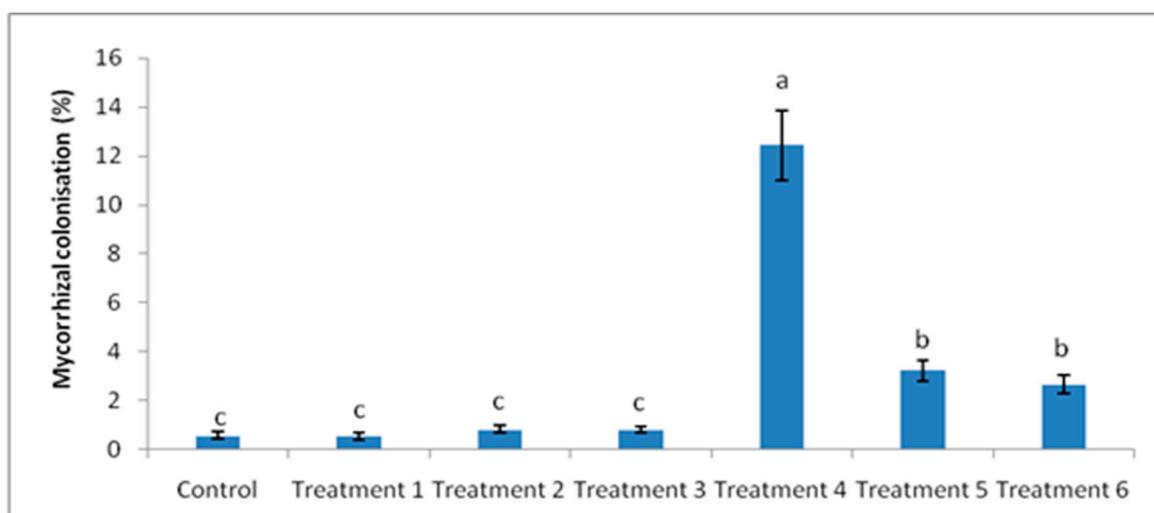


Figure 4. Effect of biochar, fertilizer and manure on percent of arbuscular mycorrhizal (AM) colonization in roots of cucumber. Different letters above the bars suggested that these values are significantly different at $p \leq 0.05$.

3.4. Biochar Effects on Soil pH and Nutrient Availability at the End of Plant Growth Cycle

After harvesting cucumber, soil pH, total organic C, N, organic matter content, and macro- and micronutrient concentrations showed significant differences in all applied treatments compared to the control (Table 4). The highest soil pH of 7.0 was observed in T3 and T4, which was statistically similar to pH of 6.9, 6.9, and 6.8 observed in plots that were treated with T1, T2, and T6, respectively, whereas, the lowest pH of 6.1 was observed in the control.

Table 4. Effect of poultry litter manure, biochar, and conventional fertilizers on soil nutrient concentrations at harvest.

Treatment	pH	N	TOC	CN	SOM	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn
	CaCl ₂	%	%	Ratio	%	mg kg ⁻¹								
Control	6.1	0.03	0.39	13.5	0.67	34	120	458	62	89	5.0	2.2	40	52
Treatment 1	6.9	0.06	0.83	14.3	1.43	58	186	633	112	119	9.8	6.5	42	64
Treatment 2	6.9	0.06	0.71	12.5	1.22	55	218	642	92	89	5.0	2.1	42	57
Treatment 3	7.0	0.05	0.65	12.8	1.12	45	168	645	110	114	8.9	4.3	41	61
Treatment 4	7.0	0.06	0.69	12.5	1.19	48	192	567	92	70	4.4	1.7	36	62
Treatment 5	6.7	0.04	0.45	12.0	0.78	42	183	565	87	30	5.3	2.4	37	43
Treatment 6	6.8	0.04	0.49	12.2	0.84	42	179	550	82	60	5.4	2.0	38	43
LSD $p < 0.05$	0.2	0.01	0.12	2.0	0.25	6	65	67	11	23	2.1	1.8	ns	6

Note: TOC, total organic carbon; C:N ratio, carbon nitrogen ratio; SOM, soil organic matter.

Soil C and N increased with application of biochar in a combination of higher doses of CPM and chemical fertilizers. The maximum concentration of N was 0.06% observed with application of T1, T2, and T4, which included biochar with higher CPM and NP, followed by 0.05% in T3 where only 13 t ha⁻¹ PLB was added. A low concentration of N was 0.04% noted with T5 and T6, which was higher than 0.03% in the control. Similarly, the percentage total organic carbon (TOC) showed the same trend with a maximum concentration of 0.83% achieved with application of T1, which was not statistically different than the concentrations in T2, whereas T5 and T6 produced significantly low C concentrations with values of 0.45 and 0.49%, respectively. The C to N ratio (C:N) increased in T1, whereas application

of all other treatments produced low C:N concentrations. Overall, the addition of biochar with CPM and NP increased the organic C concentration in soil. The presence of this organic C increased the soil organic matter (SOM) content with a maximum value of 1.43% in T1, which was statistically similar to the SOM content of T2 and T4, whereas T5 and T6 produced low SOM concentrations of 0.78 and 0.84%, respectively.

Post-harvest, soil P, K, and Ca increased with application of biochar combined with CPM only in those treatments in which a higher level of NP was applied. Maximum P and K concentrations of 58 and 218 mg kg⁻¹, respectively, were noted with T1 and T2, and this soil P concentration decreased with decreased doses of NP, although CPM and PLB were applied in substantial amounts. The amount of Ca, Mg, and S also increased positively with application of biochar combined with CPM and NP, while their concentration was low when only biochar was applied. All micronutrients, including Zn, Cu, Fe, and Mn, showed a general trend of increase with biochar application only when applied with CPM and NP, whereas their concentrations in some treatments, particularly T4 and T5, were lower than those of the other treatments and the control. These nutrients showed lower concentrations in the T6 treatment in which only 33 t ha⁻¹ PLB was used.

4. Discussion

Results of this study proved that addition of biochar enhanced leaf nutrient content and minimized nutrient runoff in the sandy soil investigated. Poultry litter biochar in combination with fertilizers and CPM produced healthy fruit, and improved cucumber growth and yield, by improving soil quality, nutrient concentration in soil, and the water-holding capacity of soil, thus making the soil conducive for better plant growth and fruit development (Figures 2 and 3). Treatments T2, T4, and T6 produced a significantly larger biomass of leaves compared to T1, T3, and T5 treatments. Although several treatments produced maximum crop biomass, farmer should choose and apply those treatments that produce maximum biomass with minimum cost and environmental issues. To improve sustainable agriculture and maximize crop yield, it may be challenging for farmers to use a high dose of chemical fertilizers because this treatment is costly. Although treatment T6 produced more leaf biomass, it produced a low cucumber yield. Thus, treatment T4, which used an appropriate ratio of all ingredients, could be an excellent source of biochar with organic and inorganic fertilizers that does not require a compromise of environmental issues. Similarly, treatment T2, with 9:5:13 t ha⁻¹ CPM, NP, and PLB, respectively, provided a maximum yield of cucumber followed by treatment T4, which included 1:2:7 t ha⁻¹ CPM, NP and PLB. These two treatments (T2 and T4) can be the most economical response of applied treatments without compromising on environmental risks, and can thus lead to sustainable agricultural production (Figure 3). Treatment T6, which included application of 33 t ha⁻¹ biochar alone, did not increase growth and yield of cucumber, and showed substantial decrease in yield after one month of its application. Furthermore, an increasing trend was noted after the passage of time which might be related to the release of much of the N from the biochar in the soil.

Growth and yield of cucumber (Figures 2 and 3) signify the effect of biochar application, either alone or in combination with poultry manure and NP fertilizers [59–61]. The increased leaf growth may be related to the highest nutrient release from biochar in soil and the greater availability of these nutrients to plant roots [62]. This outcome is also due to the liming effect of biochar in acidic soils, changes in soil microbial activities and function, improved crop water availability, and increased cation exchange capacity of soil [63]. Biochar and poultry manure improved the physical and chemical properties of soil, including soil structure, texture, soil porosity, water- and nutrient-holding capacity, soil bulk density, and cation exchange capacity of the sandy soils used in this study [64,65]. These treatments, thus, improved soil properties and made conditions conducive for plants to obtain maximum nutrients [29]. Many previous studies have revealed that different types of biochar applied alone or in combination with inorganic and organic fertilizers has potential to considerably improve soil health [12] and increase soil aggregate stability [66]. This treatment also enhances crop productivity [67,68], nutrient availability to plants [20,69], physiochemical properties of soil, and plant growth [70].

Almost all plots showed a definite increase in nutrient concentrations in leaves compared to the control where biochar was applied with CPM and NP (Table 3). Macro- and micronutrients, including N, P, K, Ca, Mg, S, Zn, Cu, Fe, and Mn, increased with application of biochar in a combination with CPM and NP fertilizer compared to the control. Maximum nutrient contents were recorded in all treatments applied with biochar in a combination with CPM and NP. The increase in nutrient concentrations in leaves can be positively influenced directly by plant nutrient uptake because of the nutrient content in biochar, its release characteristics, availability of nutrients, and enhanced uptake of nutrients [20,65]. Mulcahy et al. [71] found remarkable development in tomato growth, yield, and nutrient concentrations in plants grown in sandy soils amended with biochar. The higher amount of biochar addition with or without organic and inorganic fertilizers improved plant uptake of P, K, Ca, Zn, and Cu, in addition to the efficient use of fertilizers, due to retention, and thus reduced nutrient leaching from soil as reported earlier [3].

In the present experiment, addition of biochar with and without CPM and NP had a variable effect on root colonization with AM fungi [39,72]. The increased % root colonization in T4 might be related to the low availability of P in this treatment in comparison to all other treatments in which biochar was either added alone in a high dose or with high amounts of CPM and NP fertilizers. Nonetheless, the mechanisms regarding the effect of biochar amendments on % root colonization by AM fungi is not known with precision [29]. Reduction of AM fungi colonization with the maximum rate of biochar is in line with findings of [73], who noted a decline in AM fungi colonization when soils were amended with a greater amount of biochar. Some scientists suggest that biochar amendments can increase % AM root colonization in plant roots [74], whereas many others note a decrease in AM fungi abundance [73]. Inhibition in AM fungal root colonization after amendment with biochar might be related to improved availability of P in soil [22]. Comparable results were reported as a decline in the mycorrhizal colonization rate with P [75].

Application of biochar with and without CPM and NP considerably increased the post-harvest soil pH, N, total organic C, soil organic matter content, and the concentrations of macro- and micronutrients in soil compared to the control (Table 4). Increase in soil pH is primarily due to the alkalinity of biochar (pH 9.0) and the presence of ashes in biochar. The ashes contain reasonable amounts of oxides and hydroxides of alkali metals, which are easily dissolvable and react quickly with soil, so they rapidly increase the soil pH [76] and release free bases (K, Ca, Mg) and other ions into soil solution [12]. Sanchez et al. [77] stated that amendments of soil with biochar raised the soil pH by 0.4–1.2 pH units, and this increase was observed mainly in sandy and loamy textured soils compared to clayey soils. AN increase in soil pH was also described by other researchers [6,78,79] who documented a positive effect of biochar on acidic soils.

The available soil N and total organic C showed a varied response to the addition of biochar with and without CPM and NP fertilizer to soil. The available soil N ranged from 0.03 to 0.06% in all treatments. Treatments T1, T2, and T4 showed available N of 0.06%. The increase in available N in the biochar system was chiefly because of the increased soil N content due to the application of inorganic N fertilizer combined with PLB and CPM. In addition to the release of N from biochar and inorganic fertilizers, biochar also has the potential to adsorb ammonia (NH₃) more efficiently [80] and thus perform as a binder agent for NH₃ in soil. This property of biochar lessens the volatilization of ammonia from the soil surface. Amendment of soils with biochar promotes mineralization of organic matter [10,21] and boosts the release of nutrients such as N, P, and C [81]. Chan et al. [18] stated that higher nutrient-holding capacity of biochar improves nutrient supply to soil and plants, and reduces their leaching.

The C:N ratio showed a decrease compared to the control plots and continuously decreased in plots in which biochar was applied. The decreased C:N ratio revealed a less immobilization of N in plots where biochar with organic and inorganic fertilizers was applied. The control, which recorded the highest C:N ratio, revealed more N immobilization [82,83]. Addition of biochar with poultry manure increased the soil organic C content and, ultimately, an increase in soil organic matter and fertility of

soils was observed [84] due to the presence of biochar particles [12], aromatic C content, and recalcitrant C in the organic matter pool [85,86]. Release of more nutrients, particularly P, with organic amendments was also reported by Izhar Shafi et al. [87]. Increase in post-harvest soil macro- and micronutrient concentrations due to the application of biochar with poultry manures and inorganic NP fertilizers results from the nutrient reservoirs in highly weathered infertile sandy soils provided by biochar and manure [20], which improves the physical, chemical, and biological properties of soil [88]. A larger surface area with negative functional groups on organic matter facilitates nutrient capturing by biochar and stops their chelation with other nutrients. The presence of these nutrients in soil is strongly related to the mineralization of organic matter [21], and this mineralization process leads to nutrient release in soil solution [81].

Based on the biochar properties and nutrient concentrations, we found that the biochar produced from poultry litter materials is rich in C and can sequester more C in sandy soils when applied with NP fertilizer and poultry manure. However, the leaching of nutrients from organic and inorganic sources requires more experimental studies in sandy soils.

5. Conclusions

Results showed that application of poultry litter biochar with compound poultry manure and inorganic NP fertilizers increased yield, nutrient contents, and AM colonization, and reduced the negative impact of both macro- and micronutrient deficiency stress on cucumber growth. The results from this study indicate that the use of biochar could be an effective approach in relation to plant growth, yield, nutrient uptake, and improved soil fertility of sandy soils. However, further longer-term studies in fields of various agro-ecological conditions are needed to utilize this technology in sustainable cucumber crop production.

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