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Vine Pruning-Derived Biochar for Agronomic Benefits

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Abstract: The agronomic benefits of biochar (BC) prepared by slow pyrolysis of vine pruning residues, which are produced in large quantities in Romania, were evaluated. Three soil types, i.e., slightly alkaline fluvisol (S1), slightly acidic chernozem (S2), and strongly acidic luvisol (S3), with mean values of *pH* of 7.99, 6.26, and 5.40, were amended with BC at a volumetric ratio between BC and soil of 20/80. A greenhouse experiment was performed for 109 days to assess the effects of BC amendment on bell pepper growth. The following treatments were applied: foliar fertilizer, BC, BC + foliar fertilizer (using two concentrations of foliar fertilizer solution), and a control. Strongly alkaline BC (*pH* of 9.89 ± 0.01) had a significant positive effect on the growth performance of bell pepper plants sown in the strongly acidic soil S3. The mean values of height, collar diameter, number of leaves, and root volume of plants grown in BC-amended soil S3 without foliar treatment were significantly higher (13–72% and 14–33%, respectively) than those of plants grown in non-amended soil S3 without and with foliar treatment. This beneficial effect of BC on bell pepper plant growth was due to the changes in the soil properties. BC significantly increased (up to eight times) electrical conductivity, *pH*, soluble phosphorus, potassium, and ammonium nitrogen concentrations of soil S3, and decreased its bulk density by 51%, resulting in improved water/nutrient uptake and plant growth performance. BC had no favourable effect on the growth parameters of bell pepper plants sown in slightly alkaline soil S1, and slightly acidic soil S2.

Keywords: bell pepper growth; biochar; pyrolysis; soil amendment; vine pruning residue

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1. Introduction

Intensive agriculture in recent years can significantly reduce soil fertility and productivity [1–3]. The use of biochar (BC) derived from biomass residues as a soil amendment is a promising strategy for improving soil fertility and productivity, while simultaneously increasing soil carbon sequestration, reducing biomass residues, greenhouse gas (GHG) emissions, soil, and water pollution [2–16]. BC is an organic amendment rich in stable carbon (C), which is usually produced by slow pyrolysis of biomass, including agro-industrial residues, municipal solid waste, sewage sludge, energy crops, and algae [1–10,16–23]. Besides its relevant concentration of C (usually up to 90%), BC typically has high concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na), which can lead to improved plant growth and development [1–3,5–11,13–18,23]. Nutrient concentrations of BC derived from agro-industrial residues, e.g., wheat straw, rice straw, corncobs, wheat bran pellets, peanut shells, cotton trash, prunings, cow dung, and poultry litter, are commonly as follows: 1–20 g/kg for N, 0.02–12 g/kg for P, 0.1–26 g/kg for K, 0.2–4.4 g/kg for Ca, 0.05–6.6 g/kg for Mg, 0.1–1 g/kg for Na [1–3,5,8,11,13,18,23]. Moreover, BC is a source of micronutrients, including copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) [10].

The physical and chemical properties of BC are highly dependent on the type of biomass and pyrolysis temperature [6–8,10,16–19,21–29]. Various residues from agriculture, e.g., pruning waste, cereal straw, stover, and hulls, are widely used to produce BC [1–8,11–13,16–18,21,23,27,30–34]. These residues are usually burnt or incorporated into the soil, causing environmental concerns as well as losses of valuable nutrients and organic matter. Moreover, BC is more stable in soil than the corresponding non-pyrolyzed biomass [7,23]. BC applied as a soil amendment is commonly produced at temperatures of 300–600 °C for 45–120 min [2,5,8,11,16–18,21,23,27,29]. An increase in pyrolysis temperature usually leads to higher levels of BC porosity, specific surface area (*SSA*), water holding capacity (*WHC*), electrical conductivity (*EC*), *pH*, C and ash concentrations [5,6,8,10,14,27,35]. Usevičiūtė and Baltrėnaitė-Gedienė [36] prepared BC from five different types of lignocellulosic materials, i.e., pine wood, pine bark, birch wood, birch bark, and hemp, at nine pyrolysis temperatures (t = 300–700 °C) for 120 min. An increase in t resulted in an increase in BC properties as follows: 5.0–9.3 times in *EC* (0.04–0.42 dS/m), 1.3–1.6 times in *pH* (5.05–9.06), 56–811 times in *SSA* (0.47–421 m^2/g), 26–70 times in total pore volume (0.003–0.254 cm^3/g), 1.3–1.8 times in C concentration (47.47–92.32%), and 1.7–10.9 times in ash concentration (0.58–32.1%). Ahmad et al. [37] produced BC from soybean stover and peanut shells at 300 °C and 700 °C for 180 min. They found an increase in *pH* (7.27–11.32) of up to 1.6 times, in *SSA* (3.14–448.2 m^2/g) up to 143 times, in C concentration (68.27–83.76%) of about 1.2 times, and in ash concentration (1.24–17.18%) of up to 7.2 times with an increase in temperature. Irfan et al. [38] prepared BC from halophyte grass (*Achnatherum splendens* L.) at three levels of t (300, 500, and 700 °C) for 120 min. They reported an increase in *EC* (5.53–7.41 dS/m), *pH* (7.54–10.98), C concentration (57.71–64.43%), and ash concentration (16.96–26.59%) with an increase in temperature.

Many studies have reported that BC increased soil porosity, *SSA*, *WHC*, *EC*, *pH*, organic C concentration, cation exchange capacity (*CEC*), decreased soil bulk density (*BD*), and improved its microbiome and enzymatic activity [4–16,18,21,23,35,39,40]. Moreover, BC can be a very effective amendment for acidic soils because its *pH* typically ranges from neutral to alkaline (6.5–12.0) [4,8,10,15,16,21,35]. BC amendment can also remediate contaminated soils by retaining heavy metals [including Cu, Fe, Zn, cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb)] and other pollutants [e.g., nitrates, phosphates, antibiotics, pesticides, polycyclic aromatic hydrocarbons (PAHs)] [5,7–11,13,14,16,20,21,35].

In general, these beneficial effects of BC on soil physical, chemical, and biological properties result in improved soil nutrient retention and availability to plants and thus enhanced plant growth and yield. A positive effect of BC on growth and development of maize, wheat, durum wheat, rice, oat, sorghum, mustard, sunflower, soybeans, tomatoes, bell peppers, cucumbers, radishes, grapes, potatoes, and sweet potatoes, was reported in related studies [4–16,18,21,23,29,35,39–43]. Vaccari et al. [42] used BC (*pH* = 7.2) produced from wood (beech, hazel, oak, and birch), at a pyrolysis temperature of 500 °C, as an amendment for a strongly acidic soil (*pH* = 5.2). Field experiment results indicated that BC applied at rates of 30 and 60 t/ha increased biomass production and grain yield of durum wheat by up to 30%, with no significant differences between the two treatments being detected. Field experiments conducted by Zhang et al. [43] revealed that a strongly alkaline BC (*pH* = 10.4) prepared by slow pyrolysis of wheat straw at 350–550 °C increased grain yield of rice and wheat grown in a slightly acidic soil (*pH* = 6.5). Compared to the control, the highest increase in grain yield, i.e., by 28% for rice and 29% for wheat, was obtained for a BC application rate of 10 t/ha, whereas the increase was lower (by 9–22%) for application rates of 20 and 40 t/ha. Rehman et al. [23] studied the effect of BC obtained by slow pyrolysis of cotton stick, corncob, and rice straw at 450 °C on tomatoes grown in a moderately alkaline soil (*pH* = 8.03). Pot experiments highlighted that BC applied at rates of 34 and 68 t/ha increased shoot and root masses up to four times, the positive effect being more pronounced at the high level of BC application rate. BC retains nutrients (e.g., N, P, K, Ca, Mg, Na) and organic molecules due to its high porosity and surface functional groups [8,14]. Accordingly, nutrient losses through leaching and gaseous emissions are diminished and nutrient availability to plants increases [9,16,23]. Moreover, organic molecules retained on BC surface are decomposed by soil microorganisms, resulting in soluble inorganic nutrients that may be available to plants [8]. BC applied with either inorganic or organic fertilizer can significantly improve soil fertility and productivity [1,5–9,11,13–16,21,23,31,35,40].

The effects of BC on the soil–plant system depend on various factors, including BC and soil characteristics, BC application rate, plant species, environmental conditions, fertilizer type and application rate. Among them, soil characteristics and BC application rate substantially affect soil properties and plant growth [5,21]. Alkaline BC typically has a positive effect on the soil–plant system for soils with $pH \leq 6.5$ [15,18,21]. It is commonly applied at rates up to 100 t/ha for acidic soils [1,9,11,18,21]. Moreover, BC can also be beneficial in alkaline soils if an appropriate application rate is used [27].

This paper aimed at testing BC derived from vine pruning residues as a soil amendment. The effects of the addition of BC (56 t/ha) on the growth of bell pepper (*Capsicum annuum* L.) in three soil types (fluvisol, chernozem, and luvisol) from the Muntenia region of Romania were assessed. The same treatments were applied as in our previous study related to the growth of tomato plants [18], i.e., foliar fertilizer, BC, BC + foliar fertilizer (using two concentrations of foliar fertilizer solution), and control. Strongly alkaline BC produced from vine pruning residue and applied at a rate of 56 t/ha had a beneficial effect of tomato plants grown in luvisol strongly acidic soil, but no favourable effect on plants grown in fluvisol slightly alkaline soil and chernozem slightly acidic soil. In this study we aimed at verifying if the effects of the treatments used for growing tomatoes and bell peppers were similar. In the related literature there are only a few studies on the influence of BC addition on bell pepper growth [27,39,44,45].

Vine pruning residue was used as a BC feedstock, because it is abundant in Romania (2–4 t/ha/year) [46]. In 2020, Romania had the highest number of vineyard holdings in the EU (844,015, equivalent to 37.9% of the EU total) and was the fourth country in the EU in terms of area under vines (180,683 ha, equivalent to 5.7% of the EU total), after Spain, France, and Italy (28.5%, 24.8%, and 21.65% of the EU total) [47]. Vine residue recycling using pyrolysis could have relevant agronomic and environmental benefits. We hypothesized that BC could have beneficial effects on bell pepper growth due to improved soil properties.

2. Materials and Methods

2.1. Collection of Soils

Three medium loam soils, i.e., fluvisol (S1), chernozem (S2), and luvisol (S3), were collected from a depth of 0–20 cm from agricultural fields located in Gradistea commune (44°12′7.26″ N, 27°19′48.14″ E)—Calarasi County (S1), Perisoru commune (44°26′0.88″ N, 27°32′36.35″ E)—Calarasi County (S2), and Albota commune (44°46′31.62″ N, 24°50′31.64″ E)—Arges County (S3) [18,48]. S1 was slightly alkaline (pH of 7.99 $\pm$ 0.01), S2 slightly acidic (pH of 6.26 $\pm$ 0.02), and S3 strongly acidic (pH of 5.40 $\pm$ 0.02) [18]. The collected samples were aerated for 3 days and then ground with a soil mill to a diameter $\leq$2 mm.

2.2. Production of BC Amendment

BC was produced by slow pyrolysis of vine pruning residues, using CO_2 (purity > 99.9%) as a sweeping gas and oxidizing agent. Chopped vine branches (0.7 cm diameter and 6 cm length) were pyrolyzed in a fixed bed reactor (27 cm height, 15.5 cm internal diameter, and 3.5 cm wall thickness) at a temperature of 517 $\pm$ 16 °C for 1 h [18]. Cylindrical pieces of BC (Figure 1) were then ground with a soil mill to a diameter $\leq$2 mm.

Figure 1. BC before grinding in the soil mill.

2.3. Preparation of BC-Amended Soils

Ground soils and BC were mixed at a volumetric ratio of 80/20, resulting in BC-amended soils, i.e., S1 + BC, S2 + BC, and S3 + BC.

2.4. Greenhouse Experiment

A greenhouse experiment was performed at Research Center for Studies of Food Quality and Agricultural Products (USAMV) for 109 days (15 November 2021–4 March 2022) to evaluate the effects of BC amendment on bell pepper plant growth.

The experimental scheme (Table 1) was identical to that presented in our previous study related to tomato plant growth [18]. Accordingly, 5 treatments were applied for each soil type (a total of 15 treatments and 10 replicates per treatment). Solutions of Cropmax foliar fertilizer, either 0.2 mL/100 mL water (F) or 0.1 mL/100 mL water (F/2), were used every 12 days, 85 days after sowing (a total of 3 foliar treatments). Cropmax foliar fertilizer mainly contained N (2000 mg/L), P (4000 mg/L), K (200 mg/L), Mg (550 mg/L), Fe (200 mg/L), B (60 mg/L), Mn (54 mg/L), Zn (49 mg/L), Cu (30 mg/L), amino acids, multivitamins, enzymes, and growth stimulators.

Table 1. Treatments used in the greenhouse experiment.

No.	BC	Solution of Foliar Fertilizer		Code
		0.2 mL/100 mL Water	0.1 mL/100 mL Water	
1	-	-	-	S
2	x	-	-	S + BC
3	-	x	-	S + F
4	x	x	-	S + BC + F
5	x	-	x	S + BC + F/2

(BC) biochar; (S) soil: (F) and (F/2) foliar fertilizer (0.2 mL/100 mL water and 0.1 mL/100 mL water).

The seeds of bell pepper (*Cantemir* variety) purchased from the local market were sown in non-amended and BC-amended soils (S and S + BC), which were placed in seedling trays with 32 cells (a total of 150 cells). The indoor and outdoor temperatures, which were measured using the greenhouse compartment sensors and weather station, respectively, were collected using PRIVA CONNEXT 906 (De Lier, Netherlands) [18].

2.5. Characterization of BC Amendment, Non-Amended and BC-Amended Soils

Relevant physicochemical properties of BC amendment, non-amended and BC-amended soils are summarized in Table 2. The methods of determining these properties were detailed in our previous papers [17,18,49]. The main physicochemical parameters of non-amended and BC-amended soils were evaluated before sowing the bell peppers and 109 days after sowing. Initial levels of parameters, which were presented in our previous paper [18], are given in Table S1. All measurements were performed in triplicate.

Table 2. Relevant physicochemical properties of BC, non-amended and BC-amended soils with their symbols, units, determination techniques and equipment.

No.	Property	Symbol	Unit	Determination Technique/Equipment	Reference
1	Humidity	*HU*	%	Gravimetry	[17,18,49]
2	Bulk density	*BD*	g/cm^3	Calculated as the mass of a dried sample divided by its volume	[17,18,49]
3	pH	*pH*	-	Potentiometry/SevenExcellence pH/EC (Mettler Toledo, Columbus, OH, USA)	[17,18,49]
4	Electrical conductivity	*EC*	dS/m	Conductometry/SevenExcellence pH/EC (Mettler Toledo, Columbus, OH, USA)	[17,18,49]
5	Total carbon concentration	*C*	%	Elemental analysis/EA3100 Elemental Analyser (Eurovector, Pavia, Italy)	[17,18,49]
6	Concentration of soluble nitrate nitrogen	$N\text{-}NO_3$	mg/kg	Spectrophotometry/CECIL 2041 Spectrophotometer (Buck Scientific, Norwalk, CT, USA)	[18]
7	Concentration of soluble ammonium nitrogen	$N\text{-}NH_4$	mg/kg	Spectrophotometry/CECIL 2041 Spectrophotometer (Buck Scientific, Norwalk, CT, USA)	[18]
8	Concentration of soluble phosphorus	*P*	mg/kg	Spectrophotometry/CECIL 2041 Spectrophotometer (Buck Scientific, Norwalk, CT, USA)	[18]
9	Concentration of soluble potassium	*K*	mg/kg	Flame photometry/ Sherwood 410 Flame Photometer (Sherwood Scientific, Cambridge, UK)	[18]

2.6. Characterization of Bell Pepper Plants

Plant height (*H*), collar diameter (*CD*), number of leaves (*NL*), and root volume (*RV*) of bell pepper plants were evaluated 109 days after sowing.

2.7. Statistical Analysis

One-way ANOVA was applied to evaluate whether the addition of BC had a significant effect ($p < 0.05$) on soil physicochemical properties and whether the type of treatment (S, S + BC, S + F, S + BC + F, and S + BC + F/2) had a significant effect on plant growth parameters. The Pearson correlation coefficient (*r*) was used to assess the strength of linear correlations between the properties of non-amended and BC-amended soils. A data matrix with 6 rows (number of samples, i.e., S1, S2, S3, S1 + BC, S2 + BC, and S3 + BC) and 9 columns (number of variables, i.e., *HU*, *BD*, *pH*, *EC*, *C*, $N\text{-}NO_3$, $N\text{-}NH_4$, *P*, and *K*) was used in principal component analysis (PCA). Univariate and multivariate analyses were conducted using XLSTAT Version 2019.1 (Addinsoft, New York, NY, USA).

3. Results

3.1. Characterization of BC Amendment, Non-Amended and BC-Amended Soils

Mean values ± standard deviations (SD) of physicochemical properties of non-amended soils (S1, S2, and S3) and BC-amended soils (S1 + BC, S2 + BC, and S3 + BC) at the end of the greenhouse experiment (109 days after sowing the plants) as well as those of BC amendment [18] are given in Table 3.

Tabulated data and one-way ANOVA results indicate the following:

- mean values of humidity (*HU*), *pH*, electrical conductivity (*EC*), total carbon concentration (*C*), concentrations of soluble nitrate nitrogen ($N\text{-}NO_3$), soluble ammonium nitrogen ($N\text{-}NH_4$), soluble phosphorus and potassium (*P* and *K*) are significantly higher ($p < 0.05$) for BC-amended soils than for non-amended soils (1.2–2.0 times for

HU, 5–34% for *pH*, 23–85% for *EC*, 2.9–3.2 times for *C*, 26–85% for $N\text{-}NO_3$, 12–67% for $N\text{-}NH_4$, 1.6–10.3 times for *P*, and 3.8–12.3 times for *K*);
- mean values of bulk density (*BD*) are 16–54% lower ($p \leq 0.02$) for BC-amended soils than for non-amended soils.

Table 3. Mean values ± SD of physicochemical properties of BC amendment, non-amended soils (S), and BC-amended soils (S + BC).

No.	Property	BC	S1	S2	S3	S1 + BC	S2 + BC	S3 + BC
1	*HU* (%)	3.51 ± 0.18^{f}	7.83 ± 0.01^{d}	2.73 ± 0.04^{g}	12.53 ± 0.06^{b}	10.26 ± 0.28^{c}	5.47 ± 0.04^{e}	14.73 ± 0.18^{a}
2	*BD* (g/cm^3)	0.319 ± 0.018^{f}	1.043 ± 0.005^{b}	0.951 ± 0.050^{c}	1.280 ± 0.010^{a}	0.756 ± 0.030^{e}	0.821 ± 0.034^{de}	0.833 ± 0.027^{d}
3	*pH*	9.89 ± 0.01^{a}	8.03 ± 0.03^{d}	6.62 ± 0.04^{f}	5.40 ± 0.01^{g}	8.43 ± 0.02^{b}	8.09 ± 0.02^{c}	7.24 ± 0.02^{e}
4	*EC* (dS/m)	2.04 ± 0.07^{a}	0.20 ± 0.01^{d}	0.12 ± 0.01^{f}	0.13 ± 0.01^{f}	0.25 ± 0.01^{b}	0.22 ± 0.00^{c}	0.17 ± 0.01^{e}
5	*C* (%)	76.01 ± 0.68^{a}	2.94 ± 0.10^{d}	2.29 ± 0.12^{e}	2.20 ± 0.11^{e}	8.62 ± 0.79^{b}	7.25 ± 0.27^{c}	6.41 ± 0.60^{c}
6	$N\text{-}NO_3$ (mg/kg)	5.4 ± 0.4^{a}	2.6 ± 0.2^{c}	1.0 ± 0.2^{d}	2.2 ± 0.1^{c}	3.6 ± 0.5^{b}	1.2 ± 0.3^{d}	4.0 ± 0.4^{b}
7	$N\text{-}NH_4$ (mg/kg)	15.6 ± 1.4^{a}	2.9 ± 0.1^{d}	2.9 ± 0.4^{d}	2.7 ± 0.1^{e}	4.8 ± 0.6^{b}	3.6 ± 0.2^{c}	3.0 ± 0.2^{d}
8	*P* (mg/kg)	16.0 ± 0.3^{a}	4.2 ± 0.6^{d}	0.6 ± 0.3^{ef}	0.6 ± 0.0^{f}	11.0 ± 0.6^{b}	6.0 ± 0.6^{c}	1.0 ± 0.1^{e}
9	*K* (mg/kg)	3131.1 ± 183.0^{a}	17.8 ± 0.5^{e}	3.7 ± 0.5^{f}	4.7 ± 0.4^{f}	67.0 ± 0.8^{b}	45.6 ± 0.8^{c}	20.8 ± 1.1^{d}

(*HU*) humidity; (*BD*) bulk density; (*EC*) electrical conductivity; (*C*) total carbon concentration; ($N\text{-}NO_3$) soluble nitrate nitrogen concentration; ($N\text{-}NH_4$) soluble ammonium nitrogen concentration; (*P*) soluble phosphorus concentration; (*K*) soluble potassium concentration; (BC) biochar; (S1) fluvisol soil; (S2) chernozem soil; (S3) luvisol soil; characteristic values of physicochemical properties of non-amended and BC-amended soils were measured at the end of the greenhouse experiment; different superscript letters in the same row indicate a significant difference ($p < 0.05$).

The physicochemical properties of non-amended and amended soils were processed using PCA [18,31,50–52]. The eigenvalues corresponding to PC1 (5.92) and PC2 (1.81) were >1 and they explained 85.9% (65.8% + 20.1%) of the total variance. Data presented in Figure 2 (PCA bi-plot), Table 4 (factor loadings), and Table 5 (correlation matrix) highlight the following:

- depending on significant levels of factor loadings (highlighted in bold in Table 4), the most important variables are *K*, *EC*, *P*, *C*, $N\text{-}NH_4$, *pH*, and *BD* for PC1 as well as *HU* and $N\text{-}NO_3$ for PC2;
- BC-amended soil 1 (S1 + BC) has higher values of *K* (67.0 ± 0.8 mg/kg), *EC* (0.25 ± 0.01 dS/m), *P* (11.0 ± 0.6 mg/kg), *C* (8.62 ± 0.79%), $N\text{-}NH_4$ (4.8 ± 0.6 mg/kg), and *pH* (8.43 ± 0.02), but lower values of *BD* (0.756 ± 0.030 g/cm^3) than the other samples [discrimination on PC1 between S1 + BC (blue circle in Figure 2) and the other samples];
- non-amended and BC-amended soils 3 (S3 and S3 + BC) have higher levels of *HU* (12.53 ± 0.06% and 14.73 ± 0.18%) and $N\text{-}NO_3$ (2.2 ± 0.1 mg/kg and 4.0 ± 0.4 mg/kg) than S2 (2.73 ± 0.04% and 1.0 ± 0.2 mg/kg) and S2 + BC (5.47 ± 0.04% and 1.2 ± 0.3 mg/kg) [discrimination on PC2 (green ellipses in Figure 2)];
- *pH*, *EC*, *C*, $N\text{-}NH_4$, *P*, and *K* are directly correlated ($0.64 \leq r \leq 0.95$) and they are inversely correlated with *BD* ($-0.82 \leq r \leq -0.59$);
- *HU* is directly correlated with $N\text{-}NO_3$ ($r = 0.82$) and they are not significantly correlated with the other parameters ($-0.28 \leq r \leq 0.44$).

Table 4. Factor loadings.

Variable	PC1	PC2
HU	0.07	**0.98**
BD	**−0.81**	0.15
pH	**0.86**	−0.23
EC	**0.94**	−0.01
C	**0.92**	0.14
$N\text{-}NO_3$	0.42	**0.85**
$N\text{-}NH_4$	**0.90**	−0.05
P	**0.93**	−0.15
K	**0.97**	−0.05

(PC) principal component; (*HU*) humidity; (*BD*) bulk density; (*EC*) electrical conductivity; (*C*) total carbon concentration; ($N\text{-}NO_3$) soluble nitrate nitrogen concentration; ($N\text{-}NH_4$) soluble ammonium nitrogen concentration; (*P*) soluble phosphorus concentration; (*K*) soluble potassium concentration; significant values of factor loadings are highlighted in bold.

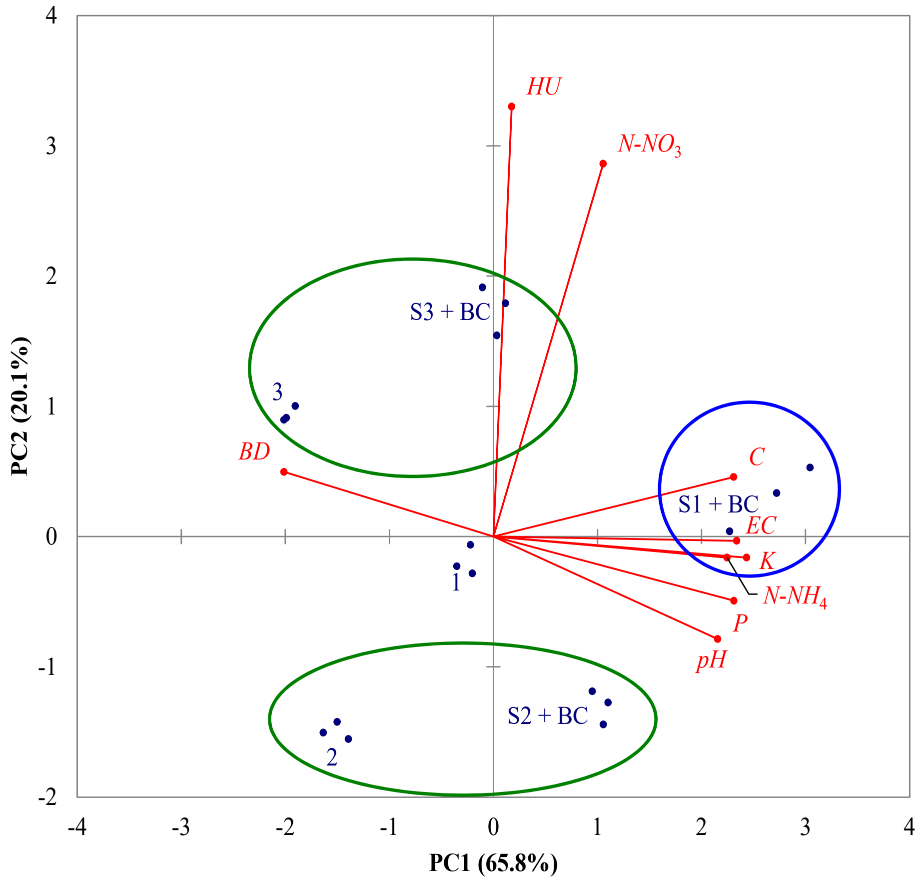


Figure 2. Projections of variables (*HU*, *BD*, *pH*, *EC*, *C*, *N-NO*$_3$, *N-NH*$_4$, *P*, and *K*) and samples (S1, S2, S3, S1 + BC, S2 + BC, and S3 + BC) on the factor-plane PC1–PC2; (*HU*) humidity; (*BD*) bulk density; (*EC*) electrical conductivity; (*C*) total carbon concentration; (*N-NO*$_3$) soluble nitrate nitrogen concentration; (*N-NH*$_4$) soluble ammonium nitrogen concentration; (*P*) soluble phosphorus concentration; (*K*) soluble potassium concentration; (BC) biochar; (S1) fluvisol soil; (S2) chernozem soil; (S3) luvisol soil.

Table 5. Correlation matrix.

Variable	*HU*	*BD*	*pH*	*EC*	*C*	N-NO$_3$	N-NH$_4$	*P*	*K*
HU	**1**								
BD	0.13	**1**							
pH	−0.20	**−0.79**	**1**						
EC	0.08	**−0.61**	**0.86**	**1**					
C	0.23	**−0.82**	**0.71**	**0.80**	**1**				
***N-NO*$_3$**	**0.82**	−0.28	0.25	0.37	0.44	**1**			
***N-NH*$_4$**	0.01	**−0.65**	**0.64**	**0.79**	**0.82**	0.31	**1**		
P	−0.07	**−0.59**	**0.78**	**0.93**	**0.76**	0.25	**0.91**	**1**	
K	0.05	**−0.73**	**0.78**	**0.93**	**0.91**	0.32	**0.90**	**0.95**	**1**

(*HU*) humidity; (*BD*) bulk density; (*EC*) electrical conductivity; (*C*) total carbon concentration; (*N-NO*$_3$) soluble nitrate nitrogen concentration; (*N-NH*$_4$) soluble ammonium nitrogen concentration; (*P*) soluble phosphorus concentration; (*K*) soluble potassium concentration; significant values of correlation coefficients at a significance level α = 0.05 (two-tailed test) are highlighted in bold.

3.2. Effects of BC Amendment on Bell Pepper Plant Growth

The values of temperatures inside and outside the greenhouse were 19.6 ± 2.2 °C and 4.6 ± 4.5 °C, respectively. The mean values ± margins of error of plant height (*H*), collar diameter (*CD*), number of leaves (*NL*), and root volume (*RV*) corresponding to 5 treatments (S, S + BC, S + F, S + BC + F, and S + BC + F/2) for each soil type, 109 days after sowing, are shown in Figure 3.

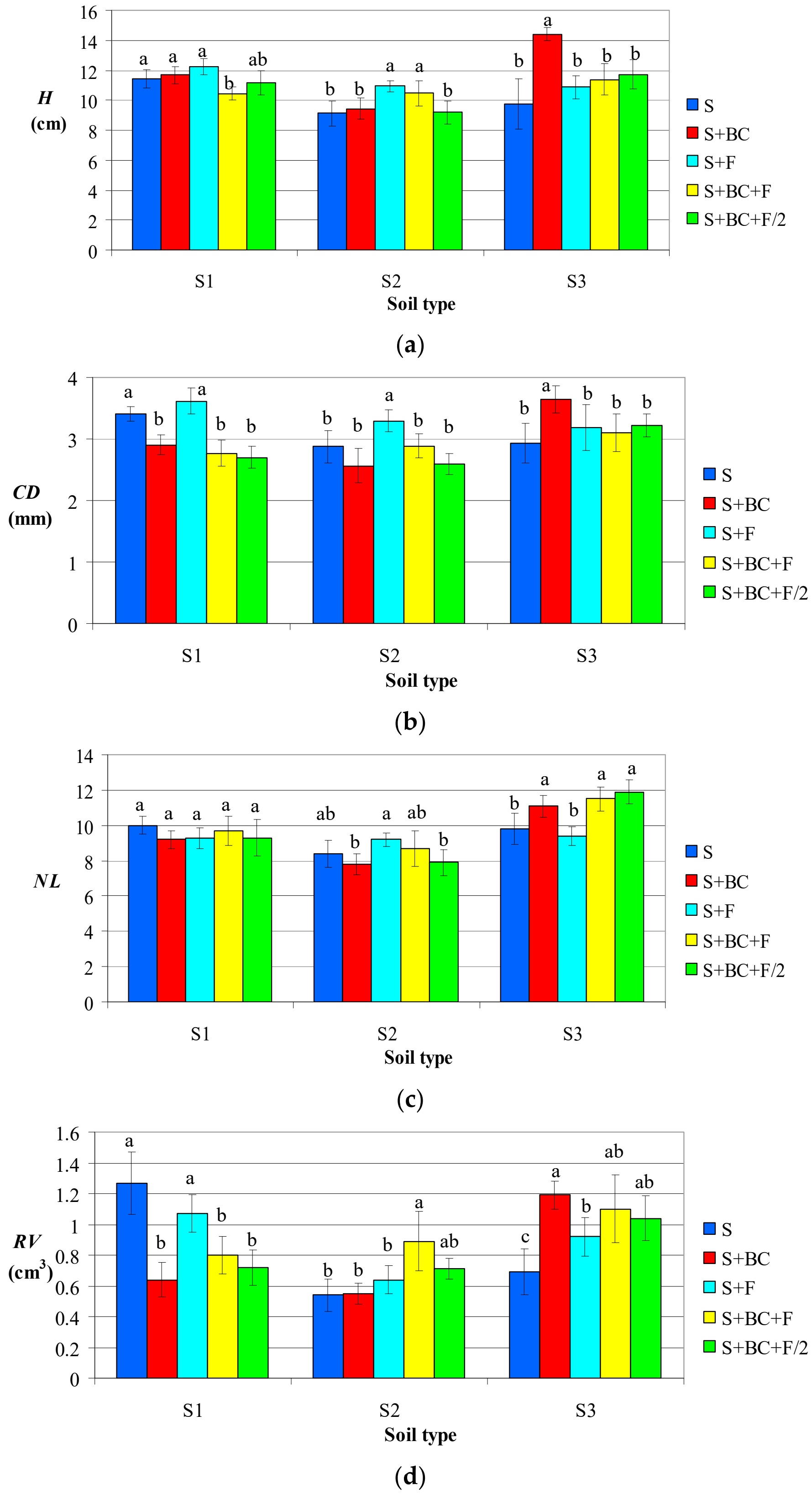


Figure 3. Mean values ± margins of error of plant height (**a**); collar diameter (**b**); number of leaves (**c**); and root volume (**d**) for different treatments, 109 days after sowing; (BC) biochar; (S1) fluvisol soil; (S2) chernozem soil; (S3) luvisol soil; (F) and (F/2) foliar fertilizer (0.2 mL/100 mL water and 0.1 mL/100 mL water); different letters corresponding to each soil type indicate a significant difference ($p < 0.05$).

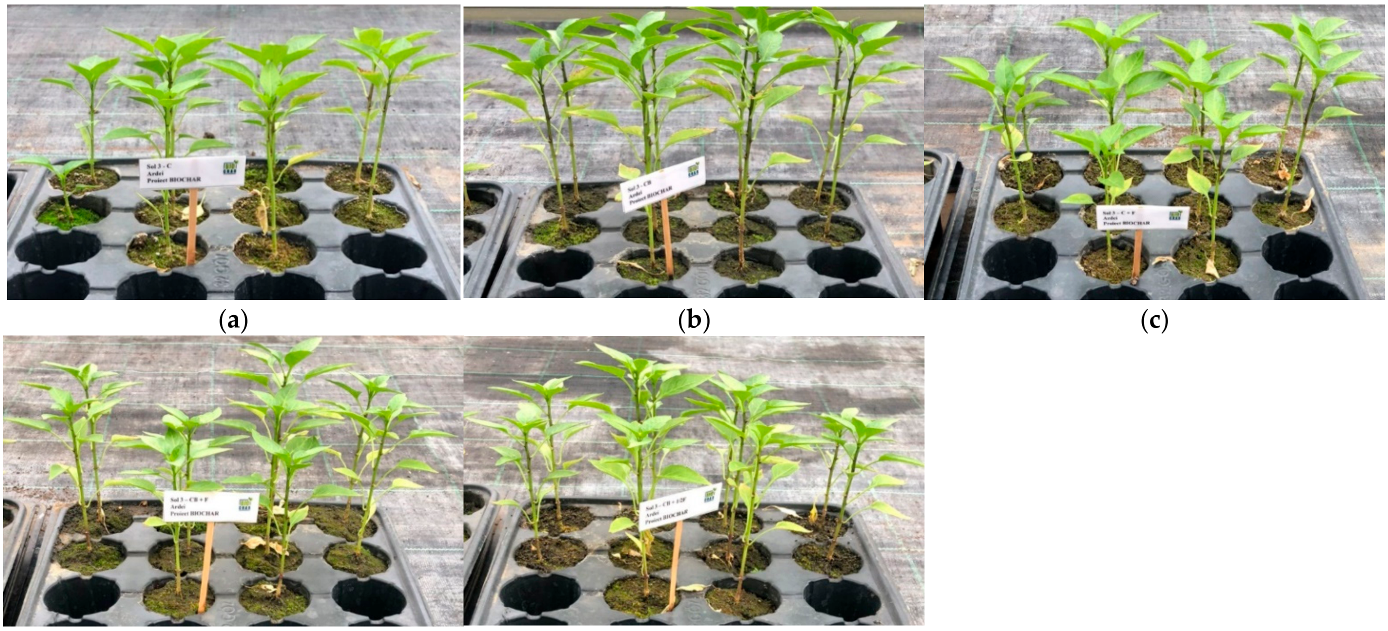
BC had a favourable effect on *H* of plants grown in soil S3 and no beneficial effect on plants grown in soil S1 (Figure 3a). The mean value of *H* corresponding to treatment S3 + BC (14.4 cm) was significantly higher (by 23–48%) than those corresponding to the other treatments (9.8–11.7 cm). The mean value of *H* corresponding to treatment S1 + BC + F (10.5 cm) was significantly lower (by 10–17%) than the mean values corresponding to treatments S1, S1 + F, and S1 + BC (11.5–12.2 cm). The mean values of *H* corresponding to treatments S2 + F (10.9 cm) and S2 + BC + F (10.5 cm) were not significantly different; they were significantly higher (by up to 20%) than those corresponding to the other treatments (9.1–9.4 cm).

BC had a beneficial effect on *CD* of plants grown in soil S3 and no favourable effect on *CD* of plants grown in soils S1 and S2 (Figure 3b). The mean value of *CD* of plants grown in BC-amended soil S3 without foliar treatment (S3 + BC), i.e., 3.6 mm, was significantly higher (by 13–24%) than those corresponding to the other treatments (2.9–3.2 mm). The mean values of *CD* of plants grown in non-amended soil S1 (3.4 mm for S1 and 3.6 mm for S1 + F) were not significantly different; they were significantly higher (by 17–34%) than those of plants grown in BC-amended soil S1 (2.7–2.9 mm). In the case of plants grown in soil S2, the mean value of *CD* corresponding to treatment S2 + F (3.3 mm) was significantly higher (by 14–28%) than those corresponding to the other treatments (2.6–2.9 mm).

BC had a favourable effect on *NL* of plants grown in soil S3 and no beneficial effect on *NL* of plants grown in soils S1 and S2 (Figure 3c). The mean values of *NL* of plants grown in BC-amended soil S3 without and with foliar treatment (11.1–11.9) were not significantly different; they were significantly higher (by 13–27%) than those corresponding to non-amended soil S3 (9.8 for untreated control S3 and 9.4 for foliar treatment S3 + F). In the case of plants grown in soil S1, the mean values of *NL* (9.2–10) were not significantly different. The mean values of *NL* of plants grown in non-amended soil S2 (S2 and S2 + F) and BC-amended soil S2 with F foliar treatment (S2 + BC + F), i.e., 8.4–9.3, were not significantly different; they were up to 19% higher than those corresponding to the other treatments.

The results presented in Figure 3d reveal that BC had a beneficial effect on *RV* of plants grown in soil S3 and a detrimental effect on *RV* of plants grown in soil S1. The mean values of *RV* of plants grown in BC-amended soil S3 without and with foliar treatment (1.04–1.19 cm^3) were not significantly different; they were significantly higher (by 51–72%) than those corresponding to untreated control S3 (0.69 cm^3); the mean value of *RV* corresponding to treatment S3 + BC (1.19 cm^3) was 29% higher (p = 0.004) than that corresponding to treatment S3 + F (0.92 cm^3). The mean values of *RV* of plants grown in non-amended soil S1 without and with foliar treatment (1.27 cm^3 and 1.07 cm^3) were not significantly different; they were significantly higher (by 34–98%) than those corresponding to BC-amended soil S1 (0.64–0.80 cm^3). The mean values of *RV* corresponding to BC-amended soil S2 with both foliar treatments (0.89 cm^3 for S2 + BC + F and 0.71 cm^3 for S2 + BC + F/2) were not significantly different; they were 11–65% higher than those corresponding to the other treatments (0.54–0.64 cm^3).

The results obtained highlighted a positive effect of strongly alkaline BC on height, collar diameter, number of leaves, and root volume of bell pepper plants grown in strongly acidic soil S3. Images of bell pepper plants grown for 109 days in non-amended and BC-amended soil S3 are presented in Figures 4 and 5. Data shown in Figure 3 indicate that strongly alkaline BC had no beneficial effect on characteristic growth parameters of plants grown in slightly alkaline soil S1 and slightly acidic soil S2.



(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 4. Images of bell pepper plants grown for 109 days in non-amended and BC-amended strongly acidic soil S3 (luvisol), applying different treatments: (**a**) S3; (**b**) S3 + BC; (**c**) S3 + F; (**d**) S3 + BC + F; and (**e**) S3 + BC + F/2; (BC) biochar; (F) and (F/2) foliar fertilizer (0.2 mL/100 mL water and 0.1 mL/100 mL water).

Figure 5. Images of bell pepper plants (root, stem, and leaves) grown for 109 days in BC-amended strongly acidic soil S3 (luvisol) without foliar treatment (S3 + BC).

4. Discussion

Strongly alkaline BC (*pH* of 9.89 ± 0.01) was produced by slow pyrolysis of vine residue at 517 ± 16 °C for 1h, in the presence of CO_2 as a sweeping gas and oxidizing agent. Three soil types, i.e., slightly alkaline soil S1 (*pH* of 7.99 ± 0.01), slightly acidic soil S2 (*pH* of 6.26 ± 0.02), and strongly acidic soil S3 (*pH* of 5.40 ± 0.02), were amended with BC at an application rate of 20/80 m^3/m^3 soil (corresponding to 56 t/ha). The agronomic benefits of BC amendment were evaluated.

On the one hand, BC had a positive effect on bell pepper plants grown in strongly acidic soil S3 (luvisol). Compared to the plants grown in non-amended soil S3 without foliar treatment (S3) and with foliar treatment (S3 + F), the mean values of height, collar diameter, number of leaves, and root volume of plants grown in BC-amended soil S3 without foliar treatment (S3 + BC) were significantly higher (by 13–72% and 14–33%, respectively. On the other hand, BC had no beneficial effect on characteristic parameters of plants grown in slightly alkaline soil S1 (fluvisol) and slightly acidic soil S2 (chernozem).

Table 6 contains data reported in this paper and in other related studies on the effects of BC on bell pepper growth and development. Mohawesh et al. [27] prepared a strongly alkaline BC by slow pyrolysis of olive tree-pruning residues (at 300–350 °C for 120 min) and tested it as an amendment for a slightly alkaline soil. Field experiment results highlighted that BC applied at rates lower than 16 t/ha enhanced bell pepper growth. Pot study performed by de Lima et al. [44] indicated that the addition of strongly alkaline BC derived from poultry litter in a strongly acidic soil (7–21 m^3/ha) had a positive effect on some growth parameters of bell pepper plant, including height, stem diameter, number and area of leaves. González-Pernas et al. [45] reported significant beneficial effects of BC on the yield of bell peppers grown in a moderately alkaline soil. BC obtained by pyrolysis of pine wood chips at 550 °C and applied at rates of 10 and 20 t/ha, without fertilizer, on plots of 3.5 m^2, led to a significant increase in the mean fresh weight of bell peppers compared with the control. Graber et al. [39] examined the effects of slightly alkaline BC produced from citrus wood on bell pepper growth and yield in a commercial soilless mixture consisting of coconut fibre and tuff. Pot experiment highlighted that plant growth and yield were significantly improved at BC application rates of 1–5% (*w*/*w*) compared with the control.

Table 6. Effects of BC on bell pepper growth and yield.

BC Type/*pH*	BC Feedstock	Soil/Other Substrate Type/*pH*	BC Application Rate	Effect of BC	Reference
strongly alkaline/ 9.89 ± 0.01	vine pruning residue	strongly acidic/ 5.40 ± 0.02	56 t/ha	BC had a beneficial effect on plant height, collar diameter, number of leaves, and root volume	this study
strongly alkaline/ 9.89 ± 0.01	vine pruning residue	slightly alkaline/ 7.99 ± 0.01; slightly acidic/ 6.26 ± 0.02;	56 t/ha	BC had no beneficial effect on plant height, collar diameter, number of leaves, and root volume	this study
strongly alkaline/ 9.50 ± 0.35	olive tree-pruning residue	slightly alkaline/ 7.7 ± 0.08	8–40 t/ha	BC applied at rates of 8 t/ha and 16 t/ha enhanced plant growth; application rates higher than 30 t/ha had a negative effect on growth performance	[27]
strongly alkaline/ 9.45	poultry litter	moderately acidic soil/ 5.75	7–21 m^3/ha	BC applied alone had a positive effect on plant height, stem diameter, number and area of leaves; an average BC dose of 19 m^3/ha was recommended	[44]

Table 6. *Cont.*

BC Type/*pH*	BC Feedstock	Soil/Other Substrate Type/*pH*	BC Application Rate	Effect of BC	Reference
moderately alkaline/ 8.6	pine wood chips	slightly alkaline/ 7.80 ± 0.06	10 and 20 t/ha	BC applied at rates of 10 t/ha and 20 t/ha, without fertilizer, led to an increase of 35.2% and 95.0% in the mean fresh weight of bell peppers compared with the control	[45]
slightly alkaline/ 7.55	citrus wood	coconut fibre + tuff (soilless mixture)	1–5% (*w*/*w*)	BC had a significant positive effect on plant growth and yield compared with the control (5:3:8 NPK fertilizer)	[39]

A similar beneficial effect of vine pruning-derived BC on height, collar diameter, number of leaves, and root volume of tomato plants grown for 66 days in strongly acidic soil luvisol was reported in our previous paper [18]. The positive effect of BC on tomato and bell pepper plant growth is due to the changes in the physicochemical properties of the soil.

Strongly alkaline BC applied as a soil amendment in this study increased *EC* and *pH* values of strongly acidic soil S3 from 0.09 ± 0.00 dS/m and 5.40 ± 0.02 to 0.16 ± 0.01 dS/m and 6.45 ± 0.11, respectively, resulting in improved nutrient availability and plant growth performance [18]. At the end of the greenhouse experiment, the mean value of *EC* (0.17 dS/m) remained almost unchanged (p = 0.23), whereas the mean value of *pH* (7.24) was 12% higher (p = 0.0003) than the initial value.

Moreover, the BC with a low mean value of *BD* (0.319 g/cm^3) significantly decreased the mean values of *BD* of soils S1, S2, and S3 by 32%, 16%, and 51%, respectively [18]. The large decrease in *BD* of strongly acidic soil S3 (from 1.314 ± 0.036 g/cm^3 to 0.873 ± 0.038 g/cm^3) led to improved plant root development and thus enhanced water/nutrient uptake and plant growth [12,18,27]. The final mean values of *BD* of all three BC-amended soils (109 days after plant sowing) were not significantly different from the initial mean values ($p > 0.05$).

Data presented in our previous study [18] indicated that BC significantly increased the concentration of soluble phosphorus (*P*), potassium (*K*), and ammonium nitrogen ($N\text{-}NH_4$) in all soil types, which can have a beneficial effect on plant growth. The values of soluble nutrient concentrations at the end of the greenhouse experiment were up to 15 times lower than the initial values, as a result of plant uptake and leaching.

Similar with the data reported for tomato plant growth in our previous paper [18], strongly alkaline BC applied at a rate of 56 t/ha had no beneficial effect on height, collar diameter, number of leaves, and root volume of bell pepper plants grown in slightly alkaline soil S1 and slightly acidic soil S2. Combining BC with other organic amendments (e.g., manure, digestate, compost) or lowering the pyrolysis temperature and/or BC dose could lead to improved plant growth performance [12,18,23,27,29].

5. Conclusions

This pot study aimed at assessing the effects of strongly alkaline BC derived from vine pruning residue on the growth performance of bell pepper plants sown in three soil types from the Muntenia region of Romania. BC had a relevant positive effect on the height, collar diameter, number of leaves, and root volume of plants grown in luvisol strongly acidic soil. This beneficial effect of BC is due to the changes in the soil physicochemical properties, including electrical conductivity, *pH*, bulk density, concentrations of soluble phosphorus, potassium, and ammonium nitrogen. The application of very strongly alkaline BC derived from vine pruning residue as an organic amendment to luvisol strongly acidic soil is a promising strategy for improving soil quality and bell pepper plant growth, while simultaneously increasing soil carbon sequestration, reducing biomass residues, and GHG emissions. BC had no favourable effect on growth parameters of bell pepper plants sown in fluvisol slightly alkaline soil and chernozem slightly acidic soil. Combining BC with other organic amendments or decreasing pyrolysis temperature and/or BC dosage could be suitable options for enhancing crop growth performance in slightly alkaline/acidic soils. Further pot/field studies on the effects of BC on bell pepper yield will be conducted.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12112730/s1, Table S1: Initial mean values ± SD of physico-chemical properties of BC amendment, non-amended soils (S), and BC-amended soils (S + BC).

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