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Impact of Carbon-Based Biochar Application on Red Pepper Yield and Soil Carbon Sequestration

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Abstract

This study investigates the impact of biochar derived from red pepper by-products on crop growth, soil carbon storage, and agricultural productivity, with a focus on adapting red pepper cultivation to climate change. The experiment was conducted over two years at the Chungcheongnam-do Agricultural Research and Extension Services in South Korea. Biochar was applied at varying rates based on its carbon content (0.0, 2.5, 5.0, 10.0 Mg C ha^{-1}) to evaluate its effects on soil properties and red pepper yield. The biochar, produced using a Top-Lit Updraft (TLUD) gasification system, possessed a carbon content of 68.7% and a high pH of 10.3. The results demonstrated that biochar application significantly enhanced red pepper growth and yield, with the highest total yield observed at the maximum application rate ($BC_{10.0}$, 10.0 Mg C ha^{-1}). However, yield efficiency (yield increase per Mg of biochar C) was highest at the lowest application rate ($BC_{2.5}$, 2.5 Mg C ha^{-1}). Soil analysis revealed that biochar amendment improved soil pH, electrical conductivity (EC), and total carbon content. Although the standard soil analysis protocol (<2 mm sieving) resulted in an underestimation of soil carbon stock by excluding coarse biochar particles, the persistence of these coarse fractions confirms the high physical stability of the biochar, validating its potential as a long-term carbon sink. These findings provide a scientific basis for optimized biochar application strategies that balance productivity with carbon sequestration.

Keywords: agricultural by-product; biochar; red pepper; soil carbon sequestration; yield efficiency

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1. Introduction

Climate change and the critical 1.5 °C warming threshold have become central to global efforts to address the climate crisis. The Paris Agreement established the goal of limiting the global temperature rise to "well below 2 °C above pre-industrial levels," while also pursuing efforts to limit the increase to 1.5 °C [1,2]. However, recent data from the EU's Copernicus Climate Change Service reported that the average global temperature had surpassed 1.5 °C above pre-industrial levels for a full year as of February 2024, marking a significant breach of this threshold [3,4].

The agricultural sector is particularly vulnerable to these climatic shifts [5]. This vulnerability poses a serious threat to long-term food supply and global food security [6]. The overall effects of climate change on major crop yields (maize, rice, soybean, wheat) are generally negative, with an estimated yield reduction of approximately 11% without adaptation measures [7]. Under severe climate change scenarios, simulated global crop yield losses are projected to range from 7% to 23% in the absence of adaptation [8].

One potential solution to mitigate these impacts is the application of biochar to agricultural land. Biochar is charred biomass produced under limited oxygen supply at high temperatures [9,10]. Due to its high content of aromatic carbon, biochar can persist in soil for centuries, acting as a long-term carbon sink [11,12]. Feedstocks for biochar production vary widely, including agricultural residues such as hay, corn stover, and rice straw [13–15]. Recognizing its potential, the Intergovernmental Panel on Climate Change (IPCC) has identified biochar as a promising Negative Emissions Technology (NET) for carbon sequestration [16].

Beyond carbon sequestration, biochar serves as a soil amendment that can enhance crop yields. Biochar typically possesses a high pH, high cation exchange capacity (CEC), and large surface area [17]. Additionally, its capacity for water and nutrient retention improves soil physicochemical properties, thereby enhancing crop productivity [18]. Meta-analyses indicate that biochar amendment typically increases crop yields by 11% to 13%, with some studies reporting increases ranging from 5% to 51% [19–23]. Given these agronomic and environmental advantages, identifying crop-specific opportunities for biochar application has become increasingly important.

Red pepper (*Capsicum annuum* L.) is one of the most important upland vegetable crops in Korea. According to a national scale assessment conducted by the Korea Rural Economic Institute (KREI), the annual generation of agricultural by-products in Korea is estimated to be approximately 93.4 million tons, among which red pepper stalks account for about 0.71 million tons per year. These red pepper cultivation residues remain largely underutilized or are disposed of through open field burning [24].

In upland red pepper production, soil degradation is a critical constraint. Long-term monocropping and intensive fertilization frequently lead to soil acidification, phosphorus over-accumulation, nutrient imbalance, and deterioration of soil structure, accompanied by changes in soil biological properties, all of which negatively affect nutrient uptake, root development, and yield stability in red-pepper-based upland systems [25].

Converting red pepper by-products into biochar provides a circular resource management strategy that simultaneously addresses residue disposal, soil quality degradation, and carbon sequestration. These issues collectively create a strong rationale for evaluating biochar derived from red pepper residues in actual red pepper cultivation systems. Despite the potential of biochar derived from red pepper residues, methodological limitations remain in current biochar research.

Most previous studies have determined biochar application rates based solely on gross weight (Mg biochar ha^{-1}), which allows uniform physical application but fails to account for equivalent carbon input. This limitation hinders a rigorous assessment of carbon sequestration efficiency and overlooks the true function of biochar as a carbon-rich amendment. Therefore, a precision agriculture approach based on biochar's carbon content is needed to more accurately evaluate its climate mitigation potential. Furthermore, achieving sustainable agriculture requires establishing a circular resource system in which agricultural by-products are recycled and returned to the land in the form of value-added inputs such as biochar.

In this study, biochar derived from red pepper by-products was applied to agricultural land based on its carbon content rather than gross weight. We investigated its effects on red pepper growth, yield, and soil carbon storage over two consecutive years. Furthermore, we evaluated both the agronomic effectiveness and carbon sequestration potential to provide scientific evidence for optimized, carbon-based biochar application strategies in response to climate change.

We hypothesized that increasing application rates of red pepper by-product biochar would improve soil physicochemical properties, enhance red pepper growth and yield, and increase soil carbon stock over the two-year experimental period.

2. Materials and Methods

2.1. Preparation for Biochar

Red pepper by-products (feedstock) were collected from Yesan, Republic of Korea. The collected biomass was air-dried in a greenhouse for approximately four weeks and subsequently cut into pieces smaller than 1–2 cm. Red pepper by-product biochar (biochar) was produced using a Top-Lit Updraft (TLUD) gasification system (Figure 1). The feedstock was pyrolyzed at approximately 450–600 °C for 3 h, and the internal temperature was monitored using a built-in sensor. Biochar yield was calculated according to Equation (1) as the mass ratio of the produced biochar to the initial feedstock [26].

$$\text{Biochar yield (\%)} = \frac{\text{W2 (g)}}{\text{W1 (g)}} \times 100 \quad (1)$$

where

- W_1: Dry mass of feedstock prior to pyrolysis
- W_2: Dry mass of biochar

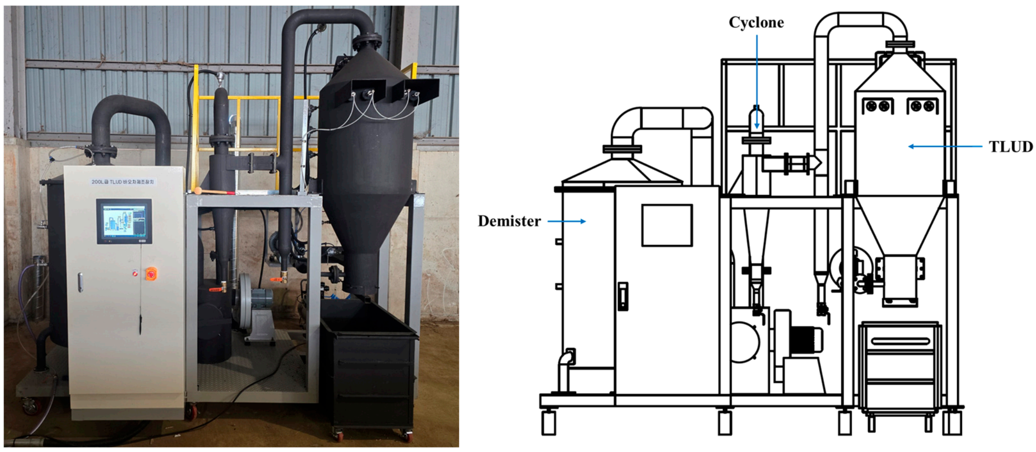

Figure 1. Experimental setup of the Top-Lit Updraft (TLUD) gasification system used for biochar production.

2.2. Field Experiment and Cultivation Management

The field experiment was conducted over two growing seasons (2022–2023) on upland soil at the Chungcheongnam-do Agricultural Research and Extension Services in Yesan, South Korea (36°44′10.9″ N, 126°49′9.8″ E) (Figure 2).

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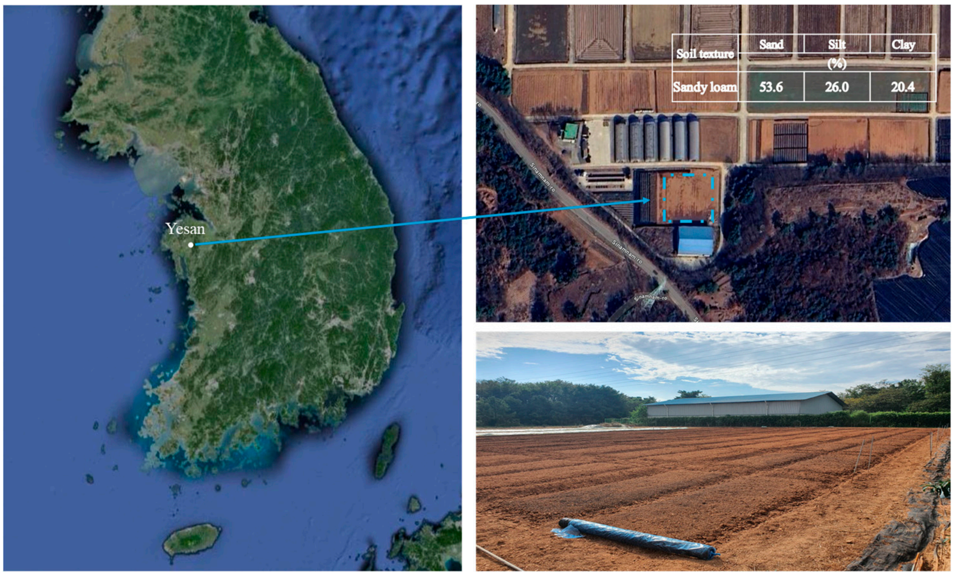

Figure 2. Map showing the location of the experimental site in Yesan, Republic of Korea.

The soil texture was sandy loam, consisting of 53.6% sand, 26.0% silt, and 20.4% clay. The initial soil chemical properties were as follows: pH 5.9, electrical conductivity (EC) 0.67 dS m^{-1}, total carbon (T-C) 1.71%, total nitrogen (T-N) 0.15%, available phosphorus (Av. P) 89 mg kg^{-1}, and exchangeable cations (K^+, Ca^{2+}, Mg^{2+}) of 0.85, 4.8, and 1.6 $cmol_c$ kg^{-1}, respectively (Table 1).

Table 1. Initial physicochemical properties of the soil at the experimental site.

Sample	Sand	Silt	Clay	Soil Texture	Bulk Density	pH	EC	T-C	T-N	Av. P	Exchangeable Cations ($cmol_c$ kg^{-1})			Soil Carbon Stock
		(%)			(Mg m^{-3})	(1:5)	(dS m^{-1})	(%)		(mg kg^{-1})	K	Ca	Mg	(Mg C ha^{-1})
Initial soil	53.6	26.0	20.4	Sandy loam	1.35	5.9 ± 0.0	0.67 ± 0.02	1.71 ± 0.11	0.15 ± 0.01	89 ± 15	0.85 ± 0.04	4.8 ± 0.1	1.6 ± 0.0	46.17

Note: Values represent the mean ± standard deviation (n = 3). EC, electrical conductivity; T-C, total carbon; T-N, total nitrogen; Av. P, available phosphorus. Soil samples were collected at a depth of 0–15 cm before treatment application.

The produced biochar had a carbon content of 68.7%. Experimental treatments were established based on this carbon content. The four treatments were designated as follows:

- NBC: Control (No biochar application)
- $BC_{2.5}$: Low application rate (2.5 Mg C ha^{-1}; corresponding to a gross weight of 3.65 Mg ha^{-1})
- $BC_{5.0}$: Medium application rate (5.0 Mg C ha^{-1}; corresponding to a gross weight of 7.3 Mg ha^{-1})
- $BC_{10.0}$: High application rate (10.0 Mg C ha^{-1}; corresponding to a gross weight of 14.6 Mg ha^{-1})

Red pepper (*Capsicum annuum* L., variety 'Jinnong') seedlings were grown in a nursery for 8 weeks and manually transplanted into experimental plots. Seedlings were planted at intervals of 100 × 40 cm spacing. Raised ridges measuring 0.5 × 0.5 m were installed to prevent cross-contamination of biochar between treatments, and the experimental plots were mulched with black polyethylene film. The study followed a Randomized Complete Block Design (RCBD) with three replicates per treatment, comprising a total of 12 plots, each measuring 20 m^2 (5.0 × 4.0 m).

Fertilization followed the standard recommendations for red pepper in Korea: urea (190 kg N ha^{-1}), superphosphate (112 kg P_2O_5 ha^{-1}), and potassium chloride (149 kg K_2O

ha^{-1}) [27]. Basal fertilizer, containing 103 kg N, 112 kg P_2O_5, and 91 kg K_2O ha^{-1}, was applied immediately after transplanting, and split applications of 43.5 kg N and 29 kg K_2O ha^{-1} were administered at 7 and 14 weeks after transplanting.

Irrigation was applied only when required to prevent severe water stress, and no artificial drainage or water-regulating treatments were implemented throughout the experiment.

Meteorological data were obtained from the Seosan Weather Station, which is the closest station to the experimental site (Figure 3).

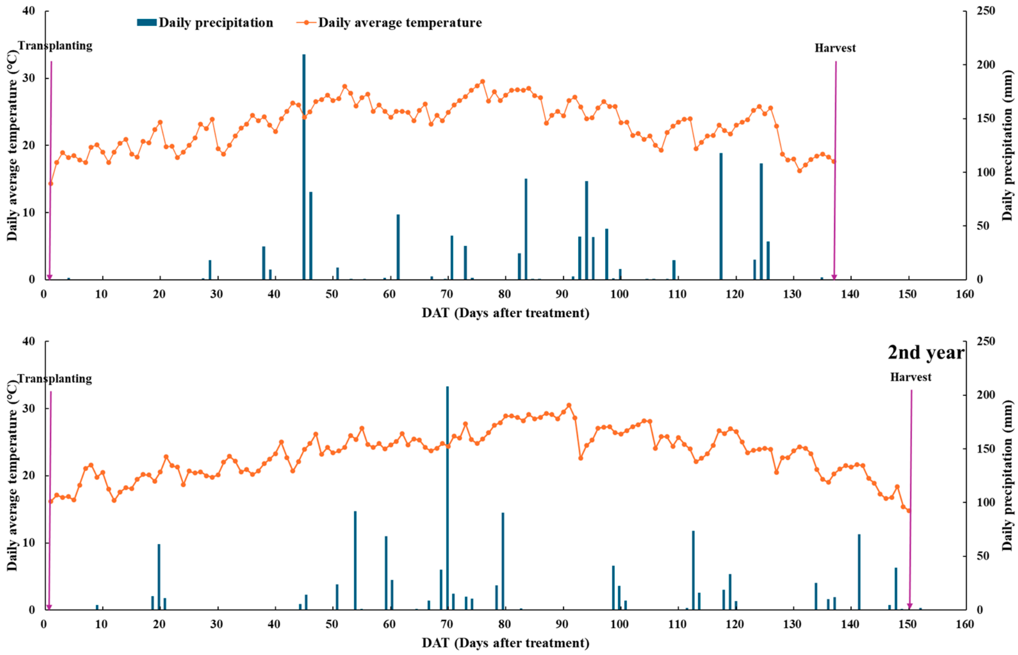

Figure 3. Daily meteorological conditions (average temperature and precipitation) during the red pepper cultivation period (2022–2023).

2.3. Biochar and Soil Analysis

2.3.1. Biochar Analysis

Biochar samples were ground and passed through a 2 mm sieve for analysis. The pH and EC were measured using a pH and EC meter (ORION™ Versa Star Pro™, Thermo Scientific Inc., Waltham, MA, USA). Elemental contents (total carbon; T-C, total nitrogen; T-N, total hydrogen; T-H) were analyzed using an elemental analyzer (Vario Micro Cube, Elementar, Langenselbold, Germany). The H/C molar ratio was calculated based on the atomic weights of hydrogen and carbon, following the Rural Development Administration (RDA) method (Equation (2)) [28].

$$\text{H/C mol ratio} = \frac{\text{H (W\%)}}{\text{C (W\%)}} \times \frac{12.01\ \text{amu}}{1\ \text{amu}} \quad (2)$$

where W% represents the mass fraction

Inorganic content (P_2O_5, K_2O, CaO, MgO) was analyzed using an inductively coupled plasma-mass spectrometer (ICP-MS; Nexion 2000, PerkinElmer, Waltham, MA, USA). Surface morphology was observed using a scanning electron microscope (SEM; FlexSEM 1000, Hitachi, Tokyo, Japan). All equipment was calibrated prior to use, and analyses were performed in triplicate.

2.3.2. Soil Analysis

Soil sampling and analysis were conducted in accordance with the 'Methods of soil and crop plant analysis' of the National Institute of Agricultural Sciences (NIAST) [29]. Soil samples were collected from ten points within each plot at a depth of 5–15 cm after removing surface organic matter and then composited. Samples were air-dried in a greenhouse for two weeks and sieved through a 2 mm mesh. As a result, coarse biochar fragments (>2 mm) were excluded, which may lead to a slight underestimation of biochar-derived carbon.

Soil samples were collected twice during the experiment: (i) prior to the establishment of the first-year trial to determine baseline soil conditions and (ii) immediately after the completion of the second-year red pepper cultivation to evaluate the cumulative effects of biochar application.

Soil texture was determined using the hydrometer method. Soil pH and EC were measured using a pH and EC meter (ORION™ Versa Star Pro™, Thermo Scientific Inc., USA). Total carbon (T-C) and total nitrogen (T-N) contents were analyzed using an elemental analyzer (Primacs, Skalar, Breda, The Netherlands). Available phosphorus (Av. P) was measured using the Lancaster method with a UV-Vis spectrophotometer (UV-1800, Shimadzu Corp., Kyoto, Japan) at 720 nm. Exchangeable cations (K^+, Ca^{2+}, Mg^{2+}) were extracted with 1 N NH_4OAc (pH 7.0) and quantified using ICP-MS (Nexion 2000, PerkinElmer, USA). All equipment was calibrated prior to use, and analyses were performed in triplicate.

2.3.3. Soil Carbon Stock Evaluation

Soil carbon stock (M) was calculated using Equation (3) based on soil carbon concentration, bulk density, and soil depth.

$$M = \frac{C}{10^3} p_b H \frac{10^4 m^2}{ha} \quad (3)$$

where

- M: Soil total carbon stock (Mg C ha^{-1})
- C: Soil carbon concentration (g C kg^{-1})
- Pb: Soil bulk density (Mg m^{-3})
- H: Soil depth (m)

The carbon retention ratio (CRR, %) represents the proportion of biochar-derived carbon retained in soil relative to the applied carbon input. It was calculated using Equation (4) [30,31].

$$CRR\ (\%) = \frac{(Mtreatment - Mcontrol)}{Capp} \times 100 \quad (4)$$

where

- $M_{treatment}$: Soil carbon stock in biochar-treated plot (Mg C ha^{-1})
- $M_{control}$: Soil carbon stock in control plot (Mg C ha^{-1})
- $M_{treatment} - M_{control}$: Net increase in soil carbon stock (Mg C ha^{-1})
- C_{app}: Applied biochar-derived carbon (Mg C ha^{-1})
- CRR: Carbon retention ratio (%)

2.3.4. Red Pepper Growth and Statistical Analysis

Red pepper growth was monitored to evaluate the effects of biochar treatments on plant development and yield. Plant growth parameters, including stem diameter, plant height, leaf length, leaf width, number of branches, and chlorophyll content, were measured 7 weeks after transplantation. Yield components, including fruit length, fruit width,

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and total yield, were evaluated every 2–3 weeks starting from 13 weeks after transplantation. Data were collected from 10 randomly selected plants per plot, following the investigation guidelines of the RDA [32].

Yield efficiency (YE) was calculated according to Equation (5) as the increase in total yield per unit of applied biochar-C, by subtracting the yield of the control (NBC) from that of each biochar treatment and dividing by the corresponding carbon application rate.

$$\text{Yield efficiency (YE)} = \frac{(\text{Yt} - \text{Yc})}{\text{Capp}} \times 100 \quad (5)$$

where

- YE: Yield efficiency (ton ha^{-1} per Mg C ha^{-1})
- Y_t: Total yield of the biochar-treated plot (ton ha^{-1})
- Y_c: Total yield of the control plot (NBC, ton ha^{-1})
- C_{app}: Applied biochar-C rate (Mg C ha^{-1})

Statistical analyses were performed using IBM SPSS Statistics version 26 (Armonk, NY, USA). Data were subjected to analysis of variance (ANOVA), and significant differences between treatment means were determined using Duncan's multiple range test at a 95% confidence level ($p \leq 0.05$).

3. Results and Discussion

3.1. Properties of Red Pepper Biochar

3.1.1. Physicochemical Properties

The biochar yield obtained from the pyrolysis of feedstock was 28.5% (Table 2). The pH of the biochar was 10.3, indicating strong alkalinity. This value aligns with previous studies reporting that biochar pH typically ranges from 9 to 12 [33,34]. The high pH is attributed to the pyrolysis process, which induces the dehydration and dehydroxylation of biomass components such as hemicellulose, cellulose, and lignin. Additionally, the volatilization of acidic substances, including acetic acid and other organic acids, leaves behind alkaline minerals, thereby increasing the pH [35]. Consequently, this high alkalinity suggests that biochar can serve as an effective soil amendment for neutralizing acidic soils and increasing phosphorus availability in agricultural lands [36].

Regarding elemental contents, the biochar exhibited a high T-C content of 68.7%. This enrichment results from the thermal decomposition process, where volatile components (H and O) are removed and recalcitrant carbon is concentrated. In addition to carbon, the biochar contained substantial amounts of essential plant nutrients, including K_2O (3.15%), CaO (2.05%), MgO (0.77%), and P_2O_5 (0.54%). These findings confirm that biochar functions not only as a carbon sink but also as a valuable source of nutrients, potentially reducing the need for chemical fertilizers.

The molar H/C ratio was 0.26, which serves as a key indicator of aromaticity. This value is well below the threshold of 0.7 required by the Korean 'Fertilizer Manufacturing Standards' [26]. A lower H/C ratio corresponds to a higher degree of aromatic condensation and structural stability, implying that the biochar is highly resistant to microbial decomposition. Therefore, the produced biochar possesses favorable characteristics for long-term soil carbon sequestration [37–39].

Table 2. Physicochemical properties of the produced red pepper by-product biochar.

Samples	pH	Elemental Content (%)			H/C Molar ratio	Inorganic Content (%)				Biochar Yield (%)
	(1:10)	T-C	T-N	T-H		P_2O_5	K_2O	CaO	MgO	
Feedstock	5.9 ± 0.1	45.1 ± 0.3	1.0 ± 0.1	5.3 ± 0.2	1.41	0.12 ± 0.1	0.74 ± 0.11	1.75 ± 0.10	0.83 ± 0.03	-
Biochar	10.3 ± 0.1	68.7 ± 0.4	2.7 ± 0.1	1.5 ± 0.2	0.26	0.54 ± 0.02	3.15 ± 0.21	2.05 ± 0.07	0.77 ± 0.02	28.5 ± 1.3

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Official standard[1)]	-	≧40	-	-	≦0.7	-	-	-	-	-

Note: Feedstock refers to red pepper by-product prior to pyrolysis. Biochar yield was calculated as the mass ratio of biochar to dry feedstock. T-C, total carbon; T-N, total nitrogen; T-H, total hydrogen.

3.1.2. Morphological Properties

Scanning Electron Microscopy (SEM) was employed to characterize the surface morphology of the feedstock and the biochar (Figure 4). The SEM images reveal a clear structural transformation following pyrolysis. The feedstock (Figure 4A,C) exhibited a coarse, fibrous, and relatively disorganized surface texture, which is typical of raw biomass.

In contrast, the biochar (Figure 4B,D) displayed a distinct morphological change. The surface appeared relatively smooth but contained a well-developed porous network beneath the surface. Specifically, at 500× magnification (Figure 4D), channel-like pores and small mineral particles on the surface were clearly visible. This porous architecture is a critical physical property of biochar, as it can increase the specific surface area.

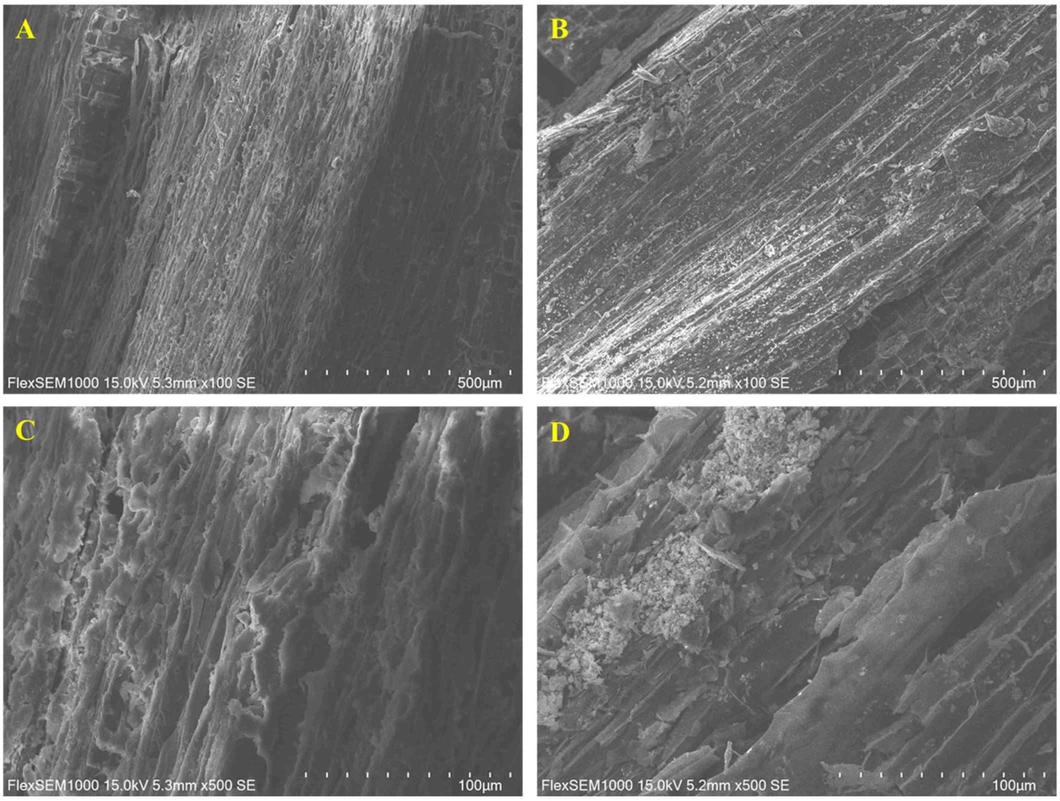

Figure 4. Scanning Electron Microscope (SEM) images of feedstock (**A**,**C**) and biochar (**B**,**D**) at different magnifications (100× and 500×). Note: Feedstock; red pepper by-product, biochar; red pepper by-product biochar.

3.2. Soil Chemical Properties

Biochar application markedly improved both the physical and chemical properties of the soil (Table 3). Previous studies have reported that biochar application can reduce soil bulk density and increase porosity, mainly through improvements in soil aggregation and pore structure [40,41]. Consistent with these findings, a clear decrease in bulk density was observed with increasing biochar application rates. The control (NBC) exhibited a bulk density of 1.43 Mg m^{-3} after two years, whereas the $BC_{10.0}$ treatment maintained a lower bulk density of 1.35 Mg m^{-3}, thereby improving soil structure and facilitating root aeration [42].

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Regarding soil chemical properties, biochar amendment effectively moderated soil acidity and improved nutrient availability. Soil pH in the biochar-treated plots ranged from 6.3 to 6.5, which was slightly higher than that of the control (6.2). This improvement is attributed to the inherent alkalinity of biochar, and such pH enhancement has been widely observed to persist over multiple years following application [43].

EC, T-N and Av. P also exhibited slight increases in the biochar-amended soils, attributable to the additional inorganic constituents supplied by the biochar [42,43].

T-C content increased proportionally with the biochar application rate. The highest T-C content (1.83%) was observed in the $BC_{10.0}$ treatment, compared with 1.64% in the control. This finding supports previous observations that recalcitrant biochar serves as a stable and persistent carbon source, contributing to long-term carbon sequestration in soils [44].

Table 3. Soil physicochemical properties after two years of biochar application.

Treatment	Bulk Density	pH	EC	Elemental Content (%)		Av. P	Exchangeable Cations ($cmol_c$ kg^{-1})			Soil Carbon Stock
	($Mg\ m^{-3}$)	(1:5, H_2O)	($dS\ m^{-1}$)	T-C	T-N	($mg\ kg^{-1}$)	K^+	Ca^{2+}	Mg^{2+}	($Mg\ C\ ha^{-1}$)
NBC	1.43	6.2 ± 0.1	0.77 ± 0.35	1.64 ± 0.04	0.16 ± 0.03	163 ± 16	1.44 ± 0.11	5.4 ± 0.1	2.2 ± 0.2	46.90
$BC_{2.5}$	1.40	6.4 ± 0.1	0.95 ± 0.10	1.73 ± 0.13	0.21 ± 0.05	164 ± 13	1.46 ± 0.09	5.6 ± 0.1	2.1 ± 0.1	48.44
$BC_{5.0}$	1.39	6.3 ± 0.1	1.02 ± 0.08	1.79 ± 0.12	0.22 ± 0.06	165 ± 12	1.42 ± 0.21	5.5 ± 0.1	2.2 ± 0.3	49.76
$BC_{10.0}$	1.35	6.5 ± 0.1	1.05 ± 0.08	1.83 ± 0.10	0.22 ± 0.04	165 ± 17	1.59 ± 0.21	5.5 ± 0.1	2.3 ± 0.1	49.41

Note: NBC, control (0 Mg C ha^{-1}); $BC_{2.5}$, $BC_{5.0}$, and $BC_{10.0}$ represent biochar application rates of 2.5, 5.0, and 10.0 Mg C ha^{-1}, respectively. Values represent the mean ± standard deviation (n = 3). EC, electrical conductivity; T-C, total carbon; T-N, total nitrogen; Av. P, available phosphorus.

3.3. Effects of Carbon-Based Biochar Application on Growth and Yield of Red Pepper

3.3.1. Growth Parameter Response to Biochar

Biochar application significantly influenced red pepper vegetative growth, particularly structural parameters such as stem diameter and branch number. In the first year (2022), stem diameter increased with application rate, ranging from 16.3 mm in the control (NBC) to 17.2 mm in $BC_{10.0}$, a 5.5% increase. The second year (2023) followed a similar pattern, though overall values were slightly reduced (Table 4). The number of branches per plant also increased from 12.8 (NBC) to 13.1 ($BC_{10.0}$), suggesting that biochar improved canopy development by promoting lateral growth.

Table 4. Effects of carbon-based biochar application on red pepper growth and yield components over two years.

Parameters		Year	Treatment			
			NBC	$BC_{2.5}$	$BC_{5.0}$	$BC_{10.0}$
Plant	Stem diameter (mm)	2022	16.3 ± 0.3 ^{C}	16.7 ± 0.2 ^{B}	17.2 ± 0.2 ^{A}	17.2 ± 0.2 ^{A}
		2023	14.1 ± 0.2 ^{c}	14.4 ± 0.3 ^{b}	14.6 ± 0.4 ^{ab}	14.7 ± 0.3 ^{a}
	Plant height (cm)	2022	115.2 ± 4.5 ^{A}	117.0 ± 3.7 ^{A}	117.3 ± 3.2 ^{A}	117.3 ± 2.1 ^{A}
		2023	110.1 ± 2.4 ^{a}	112.3 ± 2.0 ^{a}	111.4 ± 3.0 ^{a}	112.2 ± 1.7 ^{a}
	Leaf length (cm)	2022	8.3 ± 1.0 ^{A}	8.4 ± 0.5 ^{A}	8.3 ± 0.7 ^{A}	8.3 ± 0.5 ^{A}
		2023	8.3 ± 0.4 ^{a}	8.3 ± 0.4 ^{a}	8.3 ± 0.9 ^{a}	8.4 ± 0.3 ^{a}
	Leaf width (cm)	2022	3.9 ± 0.2 ^{B}	4.1 ± 0.3 ^{A}	3.8 ± 0.1 ^{B}	3.9 ± 0.2 ^{B}
		2023	3.8 ± 0.1 ^{a}	3.9 ± 0.4 ^{a}	4.0 ± 0.2 ^{a}	3.9 ± 0.3 ^{a}
	Number of branches (ea $plant^{-1}$)	2022	12.8 ± 0.2 ^{B}	13.1 ± 0.1 ^{A}	13.0 ± 0.2 ^{A}	13.1 ± 0.2 ^{A}
		2023	12.5 ± 0.2 ^{b}	12.8 ± 0.1 ^{a}	12.8 ± 0.2 ^{a}	12.9 ± 0.2 ^{a}
	Chlorophyll (SPAD)	2022	76.2 ± 3.2 ^{A}	77.3 ± 2.5 ^{A}	75.2 ± 2.7 ^{A}	77.3 ± 5.2 ^{A}
		2023	64.8 ± 2.4 ^{a}	64.3 ± 1.6 ^{a}	63.9 ± 2.5 ^{a}	64.1 ± 3.7 ^{a}

Fruit	Fruit length (cm)	2022	14.7 ± 0.5 C	15.4 ± 0.4 B	15.8 ± 0.2 A	16.0 ± 0.5 A
		2023	15.4 ± 0.4 b	16.0 ± 0.4 a	16.0 ± 0.3 a	15.8 ± 0.4 a
	Fruit width (mm)	2022	20.6 ± 0.3 C	21.0 ± 0.4 B	24.7 ± 0.2 A	24.9 ± 0.3 A
		2023	24.9 ± 0.2 c	24.9 ± 0.2 c	25.4 ± 0.1 b	25.7 ± 0.3 a
	Fruit weight (g)	2022	25.2 ± 0.7 B	27.2 ± 0.8 A	27.4 ± 0.7 A	27.5 ± 0.9 A
		2023	26.2 ± 0.5 b	27.3 ± 0.4 ab	27.2 ± 0.7 a	26.7 ± 0.8 ab
	Total yield (ton ha^{-1})	2022	33.4 ± 0.1 C	35.6 ± 0.11 B	36.2 ± 0.10 AB	37.2 ± 0.08 A
		2023	31.8 ± 0.9 c	33.0 ± 0.07 b	34.1 ± 0.10 a	34.8 ± 0.10 a
	Marketable fruit ratio	2022	92.1	91.7	92.8	91.5
		2023	85.6	84.4	85.8	84.6
	Yield index	2022	-	7.3	8.5	11.3
		2023	-	3.7	7.3	9.5

Note: NBC, control (0 Mg C ha^{-1}); $BC_{2.5}$, $BC_{5.0}$, and $BC_{10.0}$ represent biochar application rates of 2.5, 5.0, and 10.0 Mg C ha^{-1}, respectively. Values represent the mean ± standard deviation (n = 3). Different uppercase letters within a row indicate significant differences among treatments in 2022 ($p \leq 0.05$), while different lowercase letters indicate significant differences in 2023 ($p \leq 0.05$), based on Duncan's multiple range test.

These improvements are attributed to enhanced soil conditions, as shown in Section 3.2. The decrease in bulk density (from 1.43 to 1.35 Mg m^{-3}) and the slight increase in pH and nutrient availability under biochar treatments likely facilitated better root expansion and nutrient uptake, especially under the sandy loam conditions of the experimental site.

Other parameters such as plant height, leaf length, and chlorophyll content (SPAD value) showed no significant differences among treatments, though trends favored the biochar-amended plots. These results support prior findings that biochar enhances structural growth more than foliar physiology, particularly under field conditions [45,46].

3.3.2. Yield Components and Marketable Ratio

Fruit development traits also responded positively to biochar. In 2022, fruit length increased from 14.7 cm (NBC) to 16.0 cm ($BC_{10.0}$), while fruit width increased from 20.6 mm to 24.9 mm, a 20.9% increase. These size increases contributed to a higher fruit weight, rising from 25.2 g in NBC to 27.5 g in $BC_{10.0}$. The results were consistent, albeit slightly lower, in 2023 (Table 4).

$BC_{10.0}$ achieved the highest yields across both years: 37.2 ton ha^{-1} in 2022 and 34.8 ton ha^{-1} in 2023, compared to 33.4 and 31.8 ton ha^{-1} in the control, respectively. This represents an 11.3% increase in yield in the first year and 9.4% in the second year, relative to the untreated plots, and the total yield in $BC_{10.0}$ was significantly higher than that of the control according to Duncan's multiple range test ($p \leq 0.05$; Table 4).

A clear positive relationship was observed between biochar application rate and total yield, indicating that higher biochar inputs consistently promoted yield improvement across both years.

The marketable fruit ratio remained relatively stable (84–92%) across treatments and years, suggesting that biochar had a greater effect on fruit quantity than on external quality or grading. Structural improvements in plant growth did not appear to significantly impact the proportion of marketable fruit.

Despite consistent treatment effects, total yield and growth parameters were lower in 2023. In $BC_{10.0}$, for example, total yield decreased by 2.4 ton ha^{-1} compared to 2022, and similar declines were observed across all treatments. This reduction is closely associated with excessive rainfall during the first 30 days post-transplanting (Figure 3), a period critical for root establishment.

3.3.3. Yield Efficiency (Agronomic Efficiency per Mg C ha^{-1})

Yield efficiency (YE), calculated using Equation (5), revealed a contrasting trend compared to total yield. Although $BC_{10.0}$ produced the highest yield, the highest YE was observed in $BC_{2.5}$, indicating that lower biochar-C application was more efficient in terms of yield production per unit of carbon applied (Table 5). This indicates that while higher application rates maximized total yield, low to medium rates ($BC_{2.5}$–$BC_{5.0}$) resulted in better agronomic efficiency per unit of carbon applied. The decline in YE at $BC_{10.0}$ suggests that excessively high carbon inputs do not proportionally translate into yield gains, emphasizing the importance of optimizing application rates rather than maximizing them.

Table 5. Yield efficiency (YE) of red pepper as affected by biochar-C application rates.

Treatment	Total Yield Increase (vs NBC) (ton ha^{-1})	Biochar-C Rate (Mg C ha^{-1})	Yield Efficiency (YE) (ton ha^{-1} Mg C)
$BC_{2.5}$	3.22	2.5	1.29
$BC_{5.0}$	4.81	5.0	0.96
$BC_{10.0}$	5.52	10.0	0.55

3.3.4. Yearly Variability and Environmental Effects

While biochar is known to enhance water retention capacity in soil, this effect can become detrimental under excessive rainfall [47]. Sandy loam soil, which generally has low water-holding capacity, may have become overly saturated due to both biochar-induced moisture retention and heavy precipitation, leading to transient waterlogging. This condition restricts root respiration and nutrient uptake, especially oxygen diffusion into root zones [48].

These findings highlight the dual nature of biochar's hydrological effect: improvement in drought-prone systems, but potentially harmful in poorly drained or high-rainfall conditions. Hence, biochar use must be carefully calibrated to site-specific climate and soil hydrology.

3.3.5. Correlation Between Growth Traits and Yield

To clarify which growth parameters most influenced productivity, correlation analysis was conducted (Table 6). Among all measured traits, fruit width and stem diameter exhibited the strongest correlations with total yield in both years:

- Fruit width: r = +0.919 (2022), +0.794 (2023)
- Stem diameter: r = +0.840 (2022), +0.606 (2023)
- Number of branches: r = +0.442 (2022), +0.558 (2023)
- Fruit weight: r = +0.700 (2022), +0.308 (2023)

These results confirm that structural indicators—especially those tied to fruit development and support—are most predictive of yield, whereas parameters like chlorophyll content and leaf size showed weak or no significant correlation.

This supports the interpretation that biochar primarily enhances physical and reproductive plant traits through improved soil aeration, cation exchange capacity, and water balance, leading to more robust fruit development [49,50].

Table 6. Correlation coefficients between red pepper growth traits and total yield.

Parameters	2022	2023
Stem diameter	+0.840 **	+0.606 **
Plant height	+0.211	+0.251
Leaf length	−0.012	+0.080
Leaf width	−0.173	+0.132

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Number of branches	+0.442 **	+0.558 **
Chlorophyll	−0.006	−0.127
Fruit length	+0.851 **	+0.288
Fruit width	+0.919 **	+0.794 **
Fruit weight	+0.700 **	+0.308
Yield index	+0.766 **	+0.795 **

Note: Correlation coefficients (r) represent relationships between growth traits and total yield. ** indicates statistically significant correlations at $p \leq 0.01$.

Physiological studies have shown that stem diameter is closely associated with vascular development, structural support, and the plant's capacity for assimilate transport. Thicker stems generally possess greater xylem and phloem cross-sectional areas, which enhance the transport of water, nutrients, and photoassimilates to developing fruits [51,52]. These structural and functional advantages help explain the strong positive correlation observed between stem diameter and yield in this study.

Similarly, the strong correlation between fruit width and yield is consistent with well-established concepts of sink strength in fruiting crops. Wider fruits typically have a greater capacity to attract and accumulate assimilates during the reproductive phase, resulting in increased fruit mass and total yield [53,54]. These findings collectively indicate that biochar-mediated improvements in plant structure may contribute to enhanced reproductive efficiency and yield formation.

3.4. Evaluation of Soil Carbon Stock

Biochar serves as a persistent and stable carbon sink in soil environments. In this study, T-C content increased with higher biochar application rates; however, the calculated carbon stock (based on Equation (3)) was consistently lower than the theoretical carbon input from the applied biochar. This discrepancy is primarily attributed to the standard soil analysis protocol, in which samples are sieved to <2 mm, resulting in the exclusion of coarse biochar fragments (>2 mm) from carbon measurements.

The biochar applied in this study consisted of particles ranging from 1 to 2 cm, many of which remained physically intact during the two-year cultivation period and were consequently removed during sample preparation. As coarse fragments contain a substantial portion of biochar-derived carbon, their removal leads to an underestimation of the actual carbon retained in the soil. Similar methodological limitations have been noted previously, as soil carbon assessments typically capture only the fine soil fraction [17].

Although absolute values of carbon stock may therefore be conservative estimates, all treatments were subjected to identical analytical procedures. Thus, although these values were not subjected to inferential statistical testing, all treatments were evaluated using identical analytical procedures, allowing meaningful comparison of calculated trends among treatments.

Carbon Retention Ratio (CRR) and Biochar-C Preservation Efficiency

After two years of biochar application, the soil carbon stock in the control (NBC) plot was 46.90 Mg C ha^{-1}, whereas the biochar-treated plots exhibited higher values of 48.44, 49.76, and 49.41 Mg C ha^{-1} in $BC_{2.5}$, $BC_{5.0}$, and $BC_{10.0}$, respectively (Table 7). The net increase in soil carbon stock (ΔM), calculated as the difference from the control, was 1.54 Mg C ha^{-1} in $BC_{2.5}$, 2.86 Mg C ha^{-1} in $BC_{5.0}$, and 2.51 Mg C ha^{-1} in $BC_{10.0}$.

The calculated carbon retention ratio (CRR) was highest in $BC_{2.5}$ (61.6%), followed by $BC_{5.0}$ (57.2%) and $BC_{10.0}$ (25.1%). Although $BC_{10.0}$ received the highest biochar-C input (10 Mg C ha^{-1}), it showed the lowest carbon retention efficiency, indicating diminishing sequestration efficiency at higher application rates. This suggests that soil carbon stabilization capacity may be limited when excessive carbon is applied, resulting in lower preservation of biochar-derived carbon due to reduced incorporation into the fine soil fraction, physical exclusion during analysis (>2 mm), or partial mineralization.

These findings are consistent with previously reported biochar-C retention efficiencies of 20–55% in field soils [30,31], indicating that low to moderate application rates (2–5 Mg C ha^{-1}) are more effective for long-term carbon sequestration than excessively high rates.

Table 7. Applied biochar-derived carbon (C_{app}), measured increase in soil carbon stock (ΔM), and carbon retention ratio (CRR) after two years of biochar application.

Treatment	Applied Biochar-C (Mg C ha^{-1})	Soil C Stock (Mg C ha^{-1})	ΔM (Mg C ha^{-1})	CRR (%)
NBC	0	46.9	–	–
$BC_{2.5}$	2.5	48.44	1.54	61.6
$BC_{5.0}$	5	49.76	2.86	57.2
$BC_{10.0}$	10	49.41	2.51	25.1

Note: ΔM = Soil C stock in treatment − Soil C stock in control (NBC).

4. Conclusions

This study demonstrates that applying red pepper by-product biochar on a carbon-content basis provides a more precise framework for evaluating both agronomic performance and carbon sequestration potential.

(1) Biochar application improved soil chemical properties, including pH and electrical conductivity, creating more favorable conditions for red pepper growth.
(2) Red pepper yield increased with higher carbon input, whereas low-dose application ($BC_{2.5}$) achieved the highest carbon-use efficiency, suggesting a practical balance between productivity and resource efficiency.
(3) Although standard soil analysis underestimated carbon stock by excluding coarse biochar fragments (>2 mm), biochar clearly enhanced soil carbon retention, supporting its role as a persistent and stable carbon sink.
(4) Recycling agricultural residues into biochar and applying it according to carbon content offers a promising strategy to align agricultural productivity, carbon sequestration, and circular resource use. Future work should refine soil carbon assessment protocols and establish long-term monitoring frameworks.

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