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Characterization and application of biochar derived from greenhouse crop by-products for soil improvement and crop productivity in South Korea

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Abstract

The study examined the optimal production conditions and application rates of biochar derived from greenhouse crop by-products to enhance soil improvement and increase crop yield, thereby promoting sustainable agriculture in South Korea. The expansion of greenhouse cultivation has resulted in significant waste management challenges, and biochar production has emerged as a promising recycling solution for these by-products. Biochar was produced from red pepper stalks through pyrolysis at 200 to 600 °C, and its chemical properties, including pH, EC, T-C, and T-N, were analyzed. In this study, the chemical properties of biochar showed a significant increase in pH (from 5.8 to 10.3), EC (from 46.0 to 119.5 dS m^{-1}), and T-C (from 47.7 to 63.1%) with rising pyrolysis temperatures, while T-N decreased due to nitrogen volatilization above 300 °C. In the lettuce cultivation experiment, biochar application significantly improved fresh weight yield, with the biochar-treated group achieving a maximum of 83.3 g pot^{-1} in the first cropping season, compared to 62.8 g pot^{-1} in the NPK-only treatment group. However, excessive biochar application rates (≥ 800 kg ha^{-1}) led to yield reductions in the second cropping season, likely due to increased soil pH and EC. These results suggest the potential of recycling greenhouse crop residues into biochar to enhance soil fertility and crop productivity while indicating the need to manage application rates to minimize negative impacts from excessive use.

Keywords Greenhouse crop by-product, Biochar, Crop productivity

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Introduction

In the South Korea agricultural sector, approximately 12 million tons of agricultural by-products are generated annually, with an estimated 540,000 tons originating from greenhouse crop cultivation. The increasing volume of by-products from greenhouse crops is primarily attributed to the expansion of greenhouse cultivation areas in recent years [1]. While by-products from conventional agricultural fields are generally recycled or reintegrated into the soil through established practices, a significant portion of by-products from greenhouse cultivation is either incinerated or abandoned [2]. Given the stable generation of these by-products due to the continuous cultivation cycles in specific regions, there is an urgent need to develop strategies for their resource-efficient utilization.

A potential solution that has garnered attention in the context of addressing global warming is biochar production and its subsequent application. Biochar is produced through the pyrolysis of biomass, such as agricultural by-products, under oxygen-limited conditions [3]. The pyrolysis process leads to the formation of carbon-rich structures, including polycyclic aromatic forms, which can be sequestered in soil for extended periods, thereby contributing to long-term carbon storage and climate change mitigation [4–6]. Additionally, when applied to agricultural soils, biochar has demonstrated the ability to improve soil quality by enhancing pH levels, increasing nutrient and water retention capacities, and improving soil structure. Its capacity to adsorb heavy metals further underscores its efficacy as a soil amendment [5–10]. To this end, research has been conducted on the production and evaluation of biochar using various raw materials, such as waste wood, pruned branches, rice straw, and rice husks. However, there is a notable gap in studies focusing on biochar derived from greenhouse crop by-products, which represent a category of agricultural waste in critical need of sustainable resource utilization. This study seeks to address this gap by investigating the optimal production conditions and appropriate application rates of biochar derived from greenhouse crop by-products in South Korea, thereby contributing to the development of sustainable agricultural practices.

Materials and methods

Pyrolysis conditions

Greenhouse crop residues (red pepper stalks) were collected from local area (Wanju, South korea). The residues were dried at 60 °C before pyrolysis process. The dried samples were placed in porcelain crucibles and were pyrolyzed for 2 h at various temperature conditions (200, 300, 400 and 600 °C) in furnace (DK-1015, STI tech, Gumi, South Korea), into which nitrogen gas was continuously injected to maintain the oxygen-limited conditions.

Cultivation methods and crop growth assessment

A cultivation experiment was conducted at the National Institute of Agricultural Sciences in Wanju, Jeonbuk, to evaluate crop growth and soil chemical properties based on different biochar application rates. Lettuce (*Lactuca sativa* L.) was chosen as the test crop, and lettuce were grown in the pot (1 5000a^{-1}). Biochar was applied at six levels (100, 200, 400, 800, 1,000, and 2,000 kg per 10a) and evenly incorporated into the topsoil at a depth of 0–15 cm. The treatments included a control (no fertilizer, NF), an inorganic fertilizer (NPK fertilizer, NPK), and combined treatments of biochar with inorganic fertilizer (NPK+PB). Fertilizer application rates were based on the standard recommendations for lettuce by the Rural Development Administration (N-P_2O_5-K_2O=10.0-5.9-12.8 kg per 10a). Basal fertilizer (N-P_2O_5-K_2O=7.0-3.0-3.6 kg per 10a) was applied one week before transplanting, and top-dressing (N-P_2O_5-K_2O=3.5-3.0-1.8 kg per 10a) was split into two applications at 15-day intervals, starting three weeks post-transplanting. To observe crop growth characteristics relative to biochar application rates, leaf length, leaf width, leaf count, and chlorophyll content were measured twice: 30 days post-transplanting and at final harvest. Leaf length and width were averaged from the largest leaf measurements, and chlorophyll content (SPAD value) was measured with a SPAD-502 Plus (Konica Minolta, Japan) by taking five readings from the largest fully expanded leaf and averaging the values.

Soil and crop analysis

Soil chemical properties before (Table 1) and after (Table 2) crop cultivation were analyzed according to the Rural Development Administration's Soil and Plant Analysis Methods [11]. Air-dried soil passed through a 2 mm sieve was used. Soil pH and electrical conductivity (EC) were measured in a 1:5 soil-to-distilled water suspension using a pH meter (Orion 5 Star, Thermo Scientific, USA) and an EC meter (Orion Star, Thermo Scientific, USA). EC values were adjusted by the dilution factor. Available phosphorus (Av. P_2O_5) was determined using the Lancaster method with absorbance measured

Table 1 Chemical properties of soil before the experiment

	pH	EC	OM	Av. P_2O_5	K	Ca	Mg	Na
	1:5H_2O	dS m^{-1}	g kg^{-1}	mg kg^{-1}	--------------- cmol$_c$kg^{-1}----------------			
Soil	7.1	0.7	13	267	0.44	8.7	1.6	0.14

Table 2 Changes in soil chemical properties after lettuce harvesting

Treatments		**pH**	**EC**	**OM**	**Av.P_2O_5**	**K**	**Ca**	**Mg**	**Na**
		1:5H_2O	**dS m^{-1}**	**g kg^{-1}**	**mg kg^{-1}**	**----------------$cmol_c$ kg^{-1}----------------**			
NF	FC*	7.3 (0.0)bcd**	0.7 (0.0)e	12.7 (0.7)de	275 (0)cd	0.28 (0.01)e	7.1 (0.1)a	1.3 (0.1)bc	0.15 (0.00)d
	SC	7.4 (0.0)c	0.6 (0.1)c	14.5 (1.1)f	282 (3)e	0.30 (0.02)f	8.2 (0.3)a	1.6 (0.1)c	0.23 (0.02)cd
NPK	FC	7.3 (0.0)cd	0.7 (0.0)cde	13.6 (0.6)d	273 (0)d	0.26 (0.01)e	7.4 (0.2)a	1.3 (0.0)bc	0.14 (0.00)d
	SC	6.9 (0.1)d	1.5 (0.4)ab	14.2 (0.5)f	316 (7)d	0.33 (0.02)ef	8.2 (0.5)a	1.6 (0.1)c	0.20 (0.04)d
NPK +PB100	FC	7.2 (0.0)d	0.7 (0.0)de	12.5 (0.4)de	285 (5)bc	0.32 (0.01)de	7.2 (0.1)a	1.5 (0.0)a	0.16 (0.00)d
	SC	6.9 (0.1)d	1.3 (0.2)b	19.7 (0.8)ef	340 (6)c	0.42 (0.04)ef	7.8 (0.2)a	1.7 (0.0)bc	0.21 (0.00)d
NPK +PB200	FC	7.5 (0.1)ab	0.7 (0.0)cde	11.7 (0.5)e	283 (0)bcd	0.25 (0.01)e	7.4 (0.3)a	1.2 (0.0)c	0.15 (0.01)d
	SC	7.3 (0.1)c	1.1 (0.1)bc	23.8 (1.9)de	343 (7)c	0.46 (0.05)e	8.0 (0.2)a	1.6 (0.1)c	0.23 (0.01)cd
NPK +PB400	FC	7.3 (0.0)cd	0.8 (0.1)cd	12.7 (0.2)de	279 (0)cd	0.37 (0.01)d	7.2 (0.2)a	1.4 (0.0)ab	0.19 (0.01)c
	SC	7.4 (0.0)c	1.1 (0.1)bc	28.7 (0.8)d	353 (0)c	0.71 (0.02)d	8.2 (0.2)a	1.8 (0.0)bc	0.27 (0.01)bc
NPK +PB800	FC	7.3 (0.0)cd	0.8 (0.1)bc	15.6 (0.4)c	275 (0)cd	0.49 (0.02)c	7.4 (0.0)a	1.4 (0.0)ab	0.23 (0.00)b
	SC	7.8 (0.0)b	1.4 (0.2)ab	45.6 (1.4)c	400 (4)b	1.22 (0.05)c	7.9 (0.2)a	1.7 (0.0)bc	0.32 (0.01)b
NPK +PB1000	FC	7.4 (0.1)bc	0.9 (0.0)b	17.4 (0.4)b	293 (1)b	0.58 (0.03)b	7.2 (0.2)a	1.5 (0.0)a	0.24 (0.01)b
	SC	7.9 (0.0)b	1.6 (0.0)ab	51.2 (0.4)b	407 (0)b	1.52 (0.05)b	8.5 (0.2)a	1.9 (0.1)b	0.38 (0.01)a
NPK +PB2000	FC	7.6 (0.1)a	1.3 (0.0)a	20.2 (0.4)a	305 (2)a	1.06 (0.07)a	7.3 (0.0)a	1.5 (0.0)a	0.33 (0.00)a
	SC	8.5 (0.0)a	1.9 (0.1)a	82.2 (4.3)a	496 (12)a	3.03 (0.08)a	8.5 (0.2)a	2.1 (0.0)a	0.43 (0.03)a

*FC: first crop season; SC: second crop season

**Values are the means ($n=3$) with the standard deviation. Same letters indicate that the values are not significantly differed among the samples (Duncan's test, $p<0.05$)

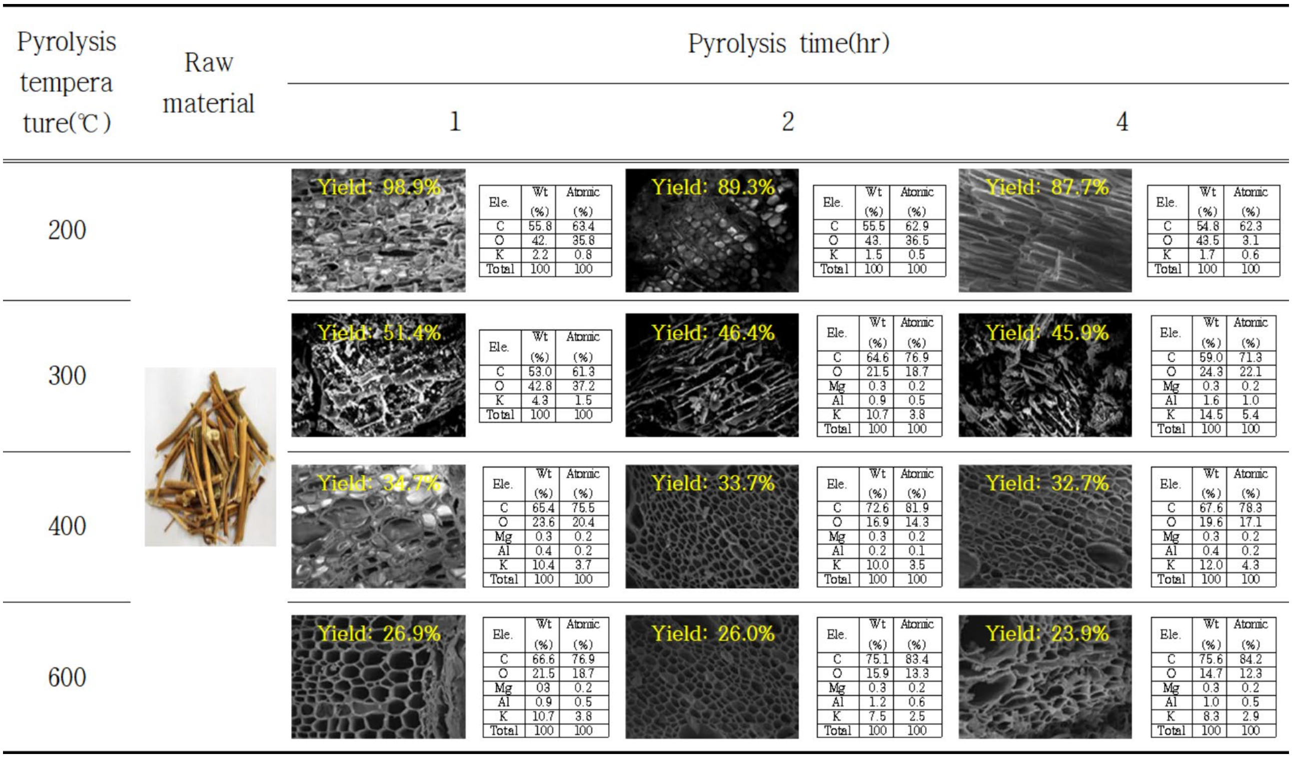
at 720 nm on a spectrophotometer (UV-1900i, Shimadzu, Japan). Exchangeable cations (Exch. K, Ca, Mg, and Na) were extracted with 1 M NH_4OAc solution and measured using an inductively coupled plasma optical emission spectrometer (ICP-OES, GBC, Australia). Soil organic matter (OM) was analyzed on a 0.5 g sample passed through a 35-mesh sieve using an elemental analyzer (Vario Max, Elementar Analysensysteme GmbH, Germany), with OM calculated by multiplying total carbon content by a conversion factor of 1.72.

Characteristics of biochar derived from greenhouse crop residue

The pH and EC of biochar were measured in a 1:25 biochar-to-distilled water suspension, stirred for 30 min and filtered using ADVANTEC No. 6 filter paper. The filtrate's pH and EC were measured with a pH meter (Orion 5 Star, Thermo Scientific, USA) and EC meter (Orion Star, Thermo Scientific, USA), respectively, with EC adjusted for the dilution factor. Total cation contents were analyzed using the microwave digestion method (Mars-X, CEM, USA) by adding 10 mL of HNO_3 to a 0.3 g sample, followed by filtration of the digest. Cations were measured using ICP-OES (GBC, Australia). Total nitrogen (T-N) and total carbon (T-C) were measured with an elemental analyzer (Vario Max, Elementar Analysensysteme GmbH, Germany).

Statistics analysis

To compare the effects of biochar application on Lettuce growth and soil chemical properties, an analysis of variance (ANOVA) was conducted using SPSS Statistics 27. Post hoc comparisons between treatments were performed with Duncan's Multiple Range Test (DMRT) at a 5% significance level.



Ele.	Wt (%)	Atomic (%)
C	55.8	63.4
O	42.	35.8
K	2.2	0.8
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	55.5	62.9
O	43.	36.5
K	1.5	0.5
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	54.8	62.3
O	43.5	3.1
K	1.7	0.6
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	53.0	61.3
O	42.8	37.2
K	4.3	1.5
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	64.6	76.9
O	21.5	18.7
Mg	0.3	0.2
Al	0.9	0.5
K	10.7	3.8
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	59.0	71.3
O	24.3	22.1
Mg	0.3	0.2
Al	1.6	1.0
K	14.5	5.4
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	65.4	75.5
O	23.6	20.4
Mg	0.3	0.2
Al	0.4	0.2
K	10.4	3.7
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	72.6	81.9
O	16.9	14.3
Mg	0.3	0.2
Al	0.2	0.1
K	10.0	3.5
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	67.6	78.3
O	19.6	17.1
Mg	0.3	0.2
Al	0.4	0.2
K	12.0	4.3
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	66.6	76.9
O	21.5	18.7
Mg	03	0.2
Al	0.9	0.5
K	10.7	3.8
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	75.1	83.4
O	15.9	13.3
Mg	0.3	0.2
Al	1.2	0.6
K	7.5	2.5
Total	100	100

Ele.	Wt (%)	Atomic (%)
C	75.6	84.2
O	14.7	12.3
Mg	0.3	0.2
Al	1.0	0.5
K	8.3	2.9
Total	100	100

Fig. 1 Characteristics and yield of biochar derived from greenhouse pepper residue depending on pyrolysis condition

Table 3 Chemical properties of biochars from red pepper (raw, biochar produced by pyrolysis at 200, 300, 400, and 600 ℃)

PT*	Time	pH	EC	T-C	T-*N*	K	Ca	Mg	Na
℃	hr	1:25H_2O	dS m^{-1}	-----%-----		---------$cmol_c$ kg^{-1}----------			
Raw		5.8	46.0	44.9	0.8	1.8	0.9	0.3	0.1
200	1	5.0c**	38.8d	47.7b	0.9b	1.7e	1.1b	0.3c	0.1abc
	2	5.2c	49.7cd	47.3b	1.0ab	2.1e	1.0b	0.3c	0.1c
	4	5.3c	44.2d	47.8b	1.0ab	1.6e	0.9b	0.3c	0.1bc
300	1	8.8b	52.0d	63.1a	1.7a	3.8c	2.0b	0.6b	0.1bc
	2	9.0b	41.5cd	62.7a	1.5ab	3.5 cd	1.9b	0.6b	0.1bc
	4	9.0b	46.9cd	62.1a	1.5ab	2.8e	5.3a	0.8a	0.3a
400	1	10.1a	58.4c	59.4ab	1.1ab	3.9c	2.1b	0.6b	0.2ab
	2	10.0a	55.9c	59.8ab	1.1ab	3.8cd	2.3ab	0.7ab	0.2ab
	4	10.0a	91.5b	61.5a	1.3ab	4.8bc	2.3ab	0.8a	0.2abc
600	1	10.2a	101.5ab	58.4ab	0.7b	5.4ab	3.0ab	0.9a	0.2abc
	2	10.2a	110.0a	60.3ab	0.7b	5.9a	3.1ab	0.8a	0.2abc
	4	10.3a	119.5a	58.1ab	0.6b	6.1a	3.1ab	0.9a	0.2abc

*PT, pyrolysis temperature

**Numbers with the same letter within a column are not significantly differed (Duncan's test, $p<0.05$)

Result and discussion

Biochar characterization

The chemical properties and yield of the biochar from red pepper stalk (raw biochar produced by pyrolysis at 200, 300, 400, and 600℃, Fig. 1), including pH, EC, T-C, T-N, and cation contents are shown in Table 3. The pH increased from 5.0 at 200℃ to 10.3 at 600℃ with the rise in pyrolysis temperature. The pH is greatly affected by the pyrolysis temperature, and it increases under high-temperature conditions [12]. The increase in pH under high-temperature conditions (above 300 ℃) can be attributed to the decomposition of organic acids, the formation and release of alkaline salts from ash, and the removal of volatile compounds, which collectively enhance the alkalinity of biochar. At a pyrolysis temperature of 200–300 ℃, cellulose and hemicellulose decompose, and organic acids and phenols are released, lowering the pH [13]. However, when the pyrolysis temperature exceeds 300 ℃, ash is produced, and alkaline salts begin to separate and be released from the organic matter, leading to an increase in the pH of the biochar [12, 14]. The EC of red pepper stalk biochars was significantly higher than that of the corresponding raw materials, and showed a significant increasing trend with increasing temperature. According to Zhang et al. [15], the EC of straw biochars increased with the increase in temperature. The increase in EC could be attributed to the increase in soluble salt content such as K and Na [16, 17]. The total carbon contents of biochars increased with increasing pyrolysis temperature, which were similar to the results obtained in other studies [2, 18, 19]. The total nitrogen content decreased with increasing pyrolysis temperature, particularly at temperatures above 300℃, where nitrogen compounds likely volatilized as NH_3 or NO_x [18, 19]. Lower pyrolysis temperatures (200–300℃) retained more nitrogen, suggesting biochar produced under these conditions may be more suitable for use as a soil amendment in nitrogen-deficient soils. Conversely, biochars from high-temperature (above 300 ℃) pyrolysis may be better suited for pH adjustment or long-term carbon sequestration due to reduced nitrogen content. The yield of biochars decreased with the increase in temperature. Lim et al. [19] reported a yield of 50% at 300 ℃, and a yield of 29.6% was observed at above 600 ℃. This result may be attributed to most of the violated matter exhalation and lingo-cellulose decomposition [20, 21].

Effect of biochar co-applied with NPK on lettuce growth and yield

Table 4; Fig. 2, and 3 show the lettuce growth and yield as affected by biochar co-applied with NPK. Statistically significant differences in lettuce growth were observed among treatments during the second year's harvest. Biochar addition increased leaf length and leaf width after harvesting. However, leaf number was not statistically different between NPK treatment and biochar co-applied with NPK treatments. The biochar co-applied with NPK treatments increased the fresh weight compared to the NPK treatment alone. in the first crop season. This is due to the effect of biochar on soil properties such as pH and CEC, thereby influencing crop production and growth [22, 23]. Previous studies have reported that the application of biochar increased the CEC due to charge density and surface area of organic matter increased [24]. In this study, lettuce growth increased as the exchangeable cation increased by biochar in the biochar co-applied with NPK treatments.

In the second crop season, fresh weight was higher in the biochar-treated groups compared to the NPK treatment. However, in the groups with biochar application amount of 800 kg or more, lettuce fresh weight decreased by 13.15% (PB800), 12.97% (PB1000), and 19.87% (PB2000) in the second crop season compared to the first. A similar trend was observed in crop yield results. In the first crop season, crop yield increased in all biochar-treated groups compared to the NPK treatment. However, in the second crop season, when the biochar application amount was 800 kg or more, crop yield decreased compared to the first crop season. This is attributed to the increase in soil pH and EC caused by the excessive addition of biochar. Biochar has high alkalinity, and excessive addition to soil can affect soil pH [25]. An increase in soil pH can reduce the availability of micronutrients such as iron, manganese, and zinc, preventing

Table 4 Growth characteristics of lettuce after harvesting under different treatments

Treatments		Fresh weight	Leaf length	Leaf width	Leaf number	SPAD
		----g----	----------cm----------		----ea----	
NF	FC[*]	37.9 (1.2)d	17.0 (0.1)c	9.3 (0.1)c	17 (0.0)b	19.9 (0.8)d
	SC	44.3 (2.5)	16.6 (0.6)bc	9.1 (0.4)b	11 (0.9)b	19.6 (2.7)c
NPK	FC	62.8 (2.5)c	19.5 (0.4)b	11.2 (0.2)b	21 (1.2)a	23.3 (1.2)c
	SC	70.1 (2.8)	18.4 (0.3)ab	10.5 (0.5)a	13 (0.3)a	30.7 (0.8)b
NPK +PB100	FC	72.3 (3.0)b	22.4 (1.1)a	12.0 (0.2)a	21 (0.6)a	24.7 (1.1)bc
	SC	76.8 (4.3)	18.9 (0.6)a	10.0 (0.1)ab	14 (0.3)a	25.2 (2.8)bc
NPK +PB200	FC	77.8 (1.1)ab	21.6 (0.0)a	12.1 (0.2)a	23 (0.6)a	25.3 (0.6)bc
	SC	82.5 (3.3)	19.0 (0.9)a	10.4 (0.6)a	13 (0.3)a	23.8 (0.6)bc
NPK +PB400	FC	75.4 (2.2)ab	21.7 (0.2)a	12.1 (0.2)a	23 (0.9)a	28.6 (0.8)a
	SC	75.2 (3.5)	17.8 (0.6)abc	9.7 (0.5)ab	14 (0.6)a	25.8 (1.5)bc
NPK +PB800	FC	82.1 (1.1)a	21.9 (0.3)a	12.0 (0.2)a	23 (0.9)a	26.1 (1.4)abc
	SC	71.3 (2.8)	16.5 (0.1)c	9.7 (0.2)ab	13 (0.3)a	25.3 (1.6)bc
NPK +PB1000	FC	83.3 (4.8)a	21.1 (0.4)ab	12.2 (0.2)a	22 (0.7)a	26.6 (0.8)ab
	SC	72.5 (0.1)	17.5 (0.3)abc	10.1 (0.0)ab	14 (0.6)a	43.6 (4.9)a
NPK +PB2000	FC	77.5 (0.8)ab	21.3 (0.8)a	12.7 (0.3)a	23 (0.3)a	24.7 (1.0)bc
	SC	62.1 (1.3)	16.4 (0.8)c	10.0 (0.4)ab	13 (0.0)a	23.7 (1.6)bc

[*] FC: first crop season; SC: second crop season

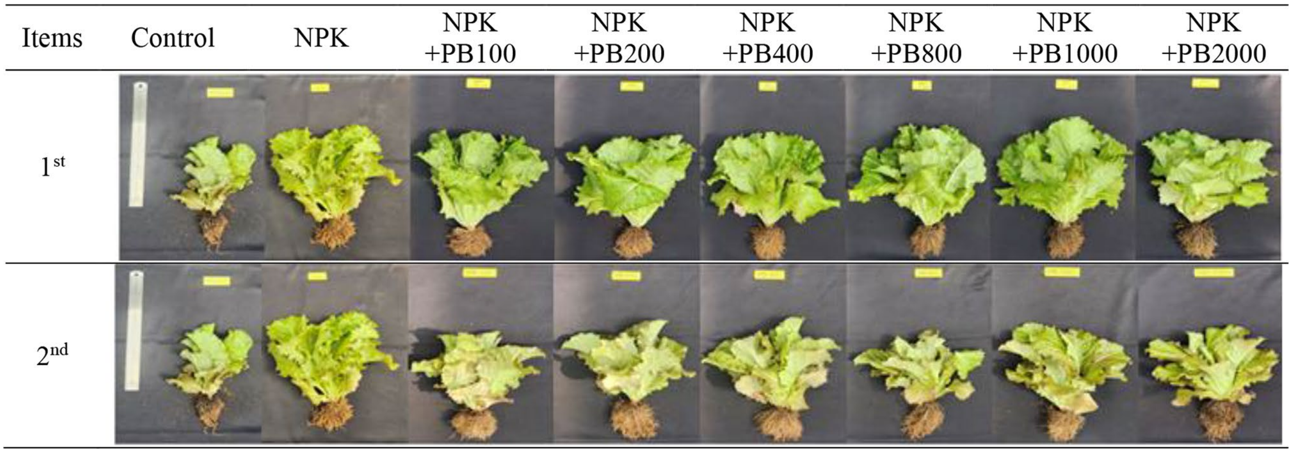


Fig. 2 Growth characteristics of lettuce harvesting under different treatments

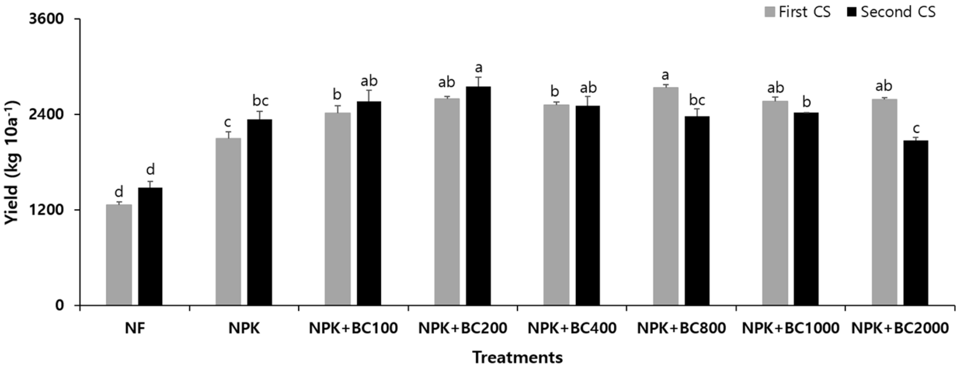


Fig. 3 Yield of lettuce after harvesting under different treatments.*FC: first crop season; SC: second crop season

plants from absorbing sufficient amounts of these essential elements [26].

Biochar affects soil fertility and crop yield. Some studies suggest that applying excessive biochar to soil may increase soil salinity in the long term [27, 28]. Although total nitrogen in soil increases with biochar application, it has also been shown that biologically available nitrogen does not significantly increase. This can lead to a stoichiometric imbalance between carbon and nitrogen in the soil [26]. These results indicate that excessive application of biochar may negatively impact crop growth and yield over long-term use. While biochar can enhance soil fertility and productivity, over-application may lead to long-term challenges, such as salinity accumulation and nutrient imbalances, which can reduce crop growth and yield. Therefore, careful management of biochar application is critical to achieving its full potential in sustainable agriculture.

Effect of inorganic fertilizer and biochar application on soil chemical properties

The changes in soil pH, electrical conductivity, organic matter, available phosphorus, and exchangeable cations of inorganic fertilizer and biochar are shown in Table 2. The pH increased with increasing biochar, and it was highest at NPK+BC 2000 both first CS and second CS. The rise of soil pH could be attributed to the high pH of the biochar (Table 3), as alkaline substances were released from the biochar into the acidic soil during the remediation process [29–31]. This effect demonstrates biochar's potential for ameliorating acidic soils. Other studies reported that the application of biochar decreased the soil EC [32, 33]. However, in this study, the soil EC increased in the second CS compared to the first CS, and it was highest at NPK+BC 2000. According to Lim et al. [34], the application of biochar increases soil salinity and sodium, leading to an increase in soil EC. Also, the soil EC increases if there is no leaching provision for the removal of salts (e.g., in a pot experiment) [35]. Exchangeable cation (K, Mg, and Na) contents increased with continuous cultivation in the application of biochar. While Ca showed no significant difference. Lehmann et al. [36] reported that the biochar in the soil can have larger negative charges on its surface, attributed to the formation of the phenolic group by abiotic oxidation, contributing to the increase of the exchangeable cation. These charges enhance cation exchange capacity (CEC), thus improving nutrient retention and availability in the soil. The soil organic matter was increased compared to the sole application of inorganic fertilizer, and it increased with increasing biochar. The highest increase was observed in the NPK+BC 2000 treatment. Biochar produced by pyrolysis has a stable carbon due to decreased volatile substances and increased carbon content and aromatic structure [6]. Therefore, the increased soil organic matter was because of the abundance of aromatic compounds in the biochar that are resistant to biological degradation [31, 37]. The results demonstrate biochar's dual role in enhancing soil properties and promoting sustainable agriculture, while also revealing risks like elevated soil salinity from excessive application. Optimizing application rates is essential to maximize benefits and minimize negative effects.

This study demonstrates the potential of biochar derived from greenhouse crop by-products in South Korea to enhance soil properties and crop productivity. Analysis of biochar produced at various pyrolysis temperatures revealed that higher temperatures led to increased pH and EC, with biochar produced at 600 °C reaching a pH of 10.3 and an EC of 119.5 dS m^{-1}. In lettuce cultivation, biochar application (co-applied with NPK fertilizer) improved growth indicators, with the fresh weight yield reaching 83.3 g in the first crop season at 1000 $kgha^{-1}$ biochar application. However, in the second season, excessive application rates (≥800 $kgha^{-1}$) resulted in yield reductions of up to 19.87% compared to the first season, likely due to soil salinity and micronutrient imbalance. These results underscore the importance of managing biochar application rates to prevent potential long-term soil salinity issues and to support the sustainable utilization of greenhouse crop by-products. While this study demonstrated the positive effects of biochar in controlled environments, further long-term field studies are needed to evaluate biochar's efficacy and impact in open-field conditions. Such research would help establish optimal application guidelines and assess biochar's sustained effects on soil properties and crop productivity, ensuring its safe and effective use in broader agricultural practices. This study provides valuable insights into biochar's role in promoting sustainable agriculture through the effective recycling of agricultural waste.

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Author contributions

Y-N L, S-S K, D-W L, J-H S, S-H J, A-S R, S-I K and S-H K designed, conducted the experiment, and contributed to manuscript writing. D-C S and S-H K provided overall inspiration, guiding the work and revising the final manuscript. All authors participated in manuscript preparation, read, and approved the final version.

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Data availability

All data is available in the main text.

Declarations

Competing interests

The authors declare that they have no competing interests. Dong-Cheol Seo is an Associate Editor of Applied Biological Chemistry.

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References

1. Lee YJ, Cho HS, Kim JY, Kang JG, Rhee SS, Kim KY (2012) Biochemical methane potential of agricul- tural residues and influence of ensiling on methane production. J Korean Soc Environ Eng 34(11):765–771
2. Kim SH, Lee DW, Jeong YJ, Byeon JE, Jeon SH, Lee YH, Kwon SI, Shim JH (2022) Characteristics of Biochars Derived from Greenhouse Crop Wastes under Different Pyrolysis Temperature and Time Conditions. Korean J Soil Sci Fert 55(4):556–562
3. Glaser B, Lehman J, Zech WZ (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Bioresour Technol 1107:419–428
4. Lehmann J (2007) A handful of carbon. Nature 447:143–144
5. Wu N, Wei H, Zhang L (2012) Efficient removal of heavy metals ions with biopolymer template synthesized mesoporous titania beads of hundreds of micrometers size. Environ Sci technol 46:419–425
6. Lee DW, Lee YN, Jeong YJ, Yun JJ, Shim JH, Jeon SH, Lee YH, Kwon SI, Kim SH (2023) Effect of biochar derived from greenhouse crop residue on lettuce growth and soil chemical properties. Korean J Soil Sci Fert 56(4):386–397
7. Verheijen F, Jeffery S, Batos AC, Van der Velde M, Diafas I (2010) Biochar application to soils-A critical scientific review of effects on soil properties, processes and functions. EUR24099 EN. European Commission, Luxembourg
8. Lehmann J, Joseph S (2009) Biochar for environmental management, science and technology. Earthscan, London, UK
9. Singh BP, Hatton BJ, Balwant S, Cowie AL, Kathuria A (2010) Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. J Environ Qual 39:1224–1235
10. Ahmad M, Lee SS, Dou X, Mohan D, Sung JK, Yang JE (2012) Effects of pyrolysis temperature on soybean stover and peanut shell derived biochar properties and TCE adsorption in water. Bioresour Technol 118:536–544
11. NIAST (National Institute of Agricultural Science and Technology) (2000) Methods of soil and plant analysis. National Institute of Agricultural Science and Technology, RDA, Suwon, Korea
12. Lee SI, Kang SS, Choi EJ, Gwon HS, Lee HS, Lee JM, Lim SS, Choi WJ (2021) Soil carbon storage in upland soils by biochar application in East Asia: Review and data analysis. Korean J Envrion Agric 40(3):219–230
13. Abe F (1988) The thermochemical study of forest biomass. Bull FFPRI 352:1–95
14. Shinogi Y, Kanri Y (2003) Pyrolysis of plant, animal, and human waste: physical and chemical characterization of the pyrolytic products. Bioresour Technol 90:241–247
15. Zhang XX, Zhang P, Yuan X, Li Y, Han L (2020) Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. Bioresour Technol 296:122318
16. Azargohar R, Nanda S, Kozinski JA, Dalai AK, Sutarto R (2014) Effects of temperature on the physicochemical characteristics of fast pyrolysis bio-chars derived from Canadian waste biomass. Fuel 125:90–100
17. Liu R, Liu G, Yousaf B, Abbas Q (2018) Operating conditions-induced changes in product yield and characteristics during thermal-conversion of peanut shell to biochar in relation to economic analysis. J Clean Prod 193:479–490
18. Baldock JA, Smernik RJ (2002) Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood. Org Geochem 33:1093–1109
19. Lim JE, Kim HW, Jeong SH, Lee SS, Yang JE, Kim KH, Ok YS (2014) Characterization of burcucumber biochar and its potential as an adsorbent for veterinary antibiotics in water. J Appl Biol Chem 57(1):65–72

20. Novak JM, Lima I, Xing B, Gaskin JW, Steiner C, Das KC (2009) Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Ann Enviorn Sci 3:195–206
21. Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS (2012) Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour Technol 107:419–428
22. Lehmann J, Pereira da Silva J, Steiner C, Nehls T, Zech W, Glaser B (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249:343–357. https://doi.org/10.1023/A:1022833116184
23. Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2008) Using poultry litter biochars as soil amendments. Soil Res 46(5):437–444
24. Major J, Steiner C, Downie A, Lehmann J (2012) Biochar effects on nutrient leaching. Biochar for environmental management, 1st edn. Routledge, pp 303–320
25. Biederman LA, Harpole WS (2013) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB bioenergy 5(2):202–214
26. Cao Y, Gao Y, Qi Y, Li J (2018) Biochar-enhanced composts reduce the potential leaching of nutrients and heavy metals and suppress plant-parasitic nematodes in excessively fertilized cucumber soils. Environ Sci Pollut Res 25:7589–7599
27. Fernandes JD, Chaves LH, Mendes JS, Chaves IB, Tito GA (2019) Alterations in soil salinity with the use of different biochar doses. Revista de Ciências Agrárias 42(1):89–98
28. Enders A, Lehmann J (2012) Comparison of wet-digestion and dry-ashing methods for total elemental analysis of biochar. Commun Soil Sci Plant Anal 43(7):1042–1052
29. Antonangelo JA, Sun X, Zhang H (2020) The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. J Enviorn Manag 277:111443
30. Shetty R, Vidya CS, Prakash NB, Lux A, Vaculik M (2021) Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. Sci Total Environ 765:142744
31. Apori SO, Byalebeka J, Murongo M, Ssekandi J, Noel GL (2021) Effect of co-applied corncob biochar with farmyard manure and NPK fertilizer on tropical soil. Resour Environ Sustain 5:100034
32. Park JH, Kim DW, Kang SW, Cho JS (2023) Effect of continuous biochar use on soil chemical properties and greenhouse gas emissions in greenhouse cultivation. Korean J Environ Agric 42(4):435–443
33. Jang JE, Lim GJ, Park JS, Shim JM, Kang CS, Hong SS (2018) Application effects of biochar derived from pruned stems of pear tree on growth of crops and soil physico-chemical properties. J Korea Org Resour Recycl 26(4):11–19
34. Lim JE, Lee SS, Ok YS (2015) Efficiency of poultry manure biochar for stabilization of metals in contaminated soil. J Appl Biol Chem 58(1):39–50
35. Saifullah, Dahlawi S, Naeem A, Rengel Z, Naidu R (2018) Biochar application for the remediation of salt-affected soils: Challenges and opportunities. Sci Total Environ 625:320–335
36. Lehmann J, Kuzyakov Y, Pan G, Ok YS (2015) Biochars and the plant-soil interface. Plant Soil 395(1–2):26
37. Phares CA, Atiah K, Frimpong KA, Danquah A, Asare AT, Aggor-Woananu S (2020) Application of biochar and inorganic phosphorus fertilizer influenced rhizosphere soil characteristics, nodule formation and phytoconstituents of cowpea grown on tropical soil. Heliyon 6(10):e05255

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