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Simultaneous enhancement of carbon sequestration and crop productivity through excessive biochar application in root vegetable (*Raphanus raphanistrum* L.) cultivation

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Abstract

Biochar, a soil amendment, is gaining attention for its potential in enhancing carbon sequestration and improving soil fertility. The conventional application rate for biochar is 2 t ha^{-1}; however, achieving maximum carbon sequestration requires higher inputs, necessitating investigation into optimal application methods to sustain crop productivity. This study evaluated the impact of a 10-times higher biochar application (20 t ha^{-1}) on root vegetable (*Raphanus raphanistrum* L.) cultivation and soil carbon sequestration, focusing on two methods broadcasting (O-BC) and band application (B-BC). The O-BC treatment improved root growth in *Raphanus raphanistrum* L. by increasing biomass and enhancing the uptake of P and K, thereby boosting productivity and nutrient assimilation. This demonstrates the key functions of P in energy transfer and root development, and K in osmoregulation and carbohydrate transport, which are crucial for root growth and development. The O-BC treatment offers the most balanced and robust enhancement of *Raphanus raphanistrum* L. growth and nutrient acquisition across plant parts. In contrast, the B-BC treatment provided only modest benefits, likely due to localized, high concentrations of biochar creating temporary imbalances in soil physicochemical properties (e.g., pH, EC) that limited optimal root development. The O-BC treatment resulted in greater biomass accumulation and enhanced P, K uptake in root tissue, leading to the highest yield (4.67 t ha^{-1}), followed by B-BC (4.51 t ha^{-1}) and the control treatment (4.28 t ha^{-1}). Biochar application at 20 t ha^{-1} enhanced soil carbon sequestration, reaching 43.75 t ha^{-1}, which is 10 times the conventional amount. These findings demonstrate that a high amount of biochar applications with the optimal application method, can effectively overcome the potential risks of high-rate application and improve root vegetable productivity while simultaneously contributing to long-term climate mitigation through increased carbon sequestration.

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Keywords Carbon sequestration, Excessive biochar application, Radish, *Raphanus raphanistrum* L., High-temperature biochar

Introduction

Carbon sequestration captures and stores atmospheric CO_2 in natural sinks such as soils, forests, and oceans, playing a critical role in mitigating climate change by lowering greenhouse gases (GHGs). To support this, various low-carbon technologies including carbon farming practices such as cover cropping, conservation tillage, and biochar application are being adopted to enhance soil health, improve nutrient and water retention, and strengthen both emissions reduction and agricultural productivity, aligning with global efforts toward carbon neutrality by 2050 [1, 2].

Biochar is a carbon-rich substance produced through biomass pyrolysis under limited oxygen conditions. Typically derived from agricultural and livestock waste, biochar has demonstrated multiple benefits, including improved soil fertility and crop productivity, enhanced carbon sequestration, and reduced GHG emissions [3–10]. In April 2024, the Rural Development Administration (RDA) of the Republic of Korea announced and implemented the Fertilizer Legal Standards for biochar, made from agricultural residues and livestock manure, to improve soil and reduce GHGs.

To maximize carbon sequestration in agricultural sector, it is necessary to apply more biochar than the conventional amount (2–5 t ha^{-1}) [11–13]. However, some researchers have reported that the excessive application of biochar potentially inhibits the growth of certain crops, indicating the need for systematic carbon sequestration techniques. Kang et al. (2017) reported that corn grown with 5–20 t ha^{-1} of biochar derived from corn byproducts showed improved corn growth compared to the control [12]. A meta-analysis by Jeffery et al. (2011) found that biochar application could increase crop yield by up to 39% when applied at amounts as high as 100 t ha^{-1}, indicating potential positive effects of high biochar treatments under certain conditions [14]. In contrast, Oh et al. (2017) reported that applying woody biochar at 90 t ha^{-1} inhibited Chinese cabbage growth at amounts above 54 t ha^{-1}, attributing the adverse effect to elevated soil pH [15]. Lee et al. (2024) investigated that the band application of biochar at an amount of 20 t ha^{-1}, which concentrates biochar in targeted soil zones, increased nutrient availability. As a result, the study found that this application method maximized carbon sequestration and maintained or improved lettuce yields, demonstrating its effectiveness in simultaneously delivering environmental and agricultural benefits [16].

Field research on biochar has largely concentrated on leafy vegetables, particularly lettuce and Chinese cabbage, as their characteristics are easily observable. Lettuce is often chosen for cultivation tests due to its rapid growth and relatively short cultivation cycles. Leafy vegetables have a high nutrient (mainly N) demand to support an increase in leaf yield and chlorophyll synthesis. They are sensitive to changes in soil pH and EC, as physicochemical alterations in the soil, including those induced by biochar application, can affect the availability of essential nutrients such as N, K, Ca, and other elements [12, 15, 16, 34].

In contrast, root vegetables such as radish (*Raphanus sativus* L.) and carrot (*Daucus carota* L.) allocate a major proportion of assimilated carbon to the development of storage roots. This morphological strategy requires extended cultivation to support the progressive thickening and physiological maturation of storage tissues, which in turn determines both yield and quality [17–19].

Unlike leafy vegetables, root crops have greater demands for P and K, which are essential for root cell division and starch accumulation. In contrast, excessive N often promotes disproportionate leaf growth at the expense of root yield, producing underdeveloped or less dense roots. Although root vegetables may not show immediate visual symptoms of nutrient deficiencies in their shoots, an imbalanced nutrient supply can still significantly impact root quality, including shape, size, and internal composition [20–22]. Given these fundamental differences in nutrient partitioning and requirements compared to leafy crops, research specific to root vegetables is essential to develop optimized biochar application guidelines.

Although extensive research has examined the effects of varying biochar application amounts, few studies have addressed the influence of different application methods. As interest in biochar continues to grow due to its potential for enhancing soil fertility and mitigating climate change through carbon sequestration, establishing more practical guidelines for its use in agricultural systems has become increasingly important. While high application amounts of biochar can significantly enhance soil carbon sequestration, they may also negatively affect soil properties and crop productivity [15], posing a barrier to its widespread adoption in farming practices. Critically, recent studies have suggested that specific application methods, such as banding, may mitigate the adverse effects of high application rates while maintaining the benefits of carbon sequestration [16].

In order to enhance carbon sequestration and optimize biochar application methods in root vegetable cultivation, this study investigated the effects of excessive amount of

biochar, applied at 10 times the conventional application amount (20 t ha^{-1}), on *Raphanus raphanistrum* L. productivity and carbon sequestration under banding and broadcasting fertilization methods. This research focused on the following objectives: (1) to compare *Raphanus raphanistrum* L. growth characteristics, nutrient uptake, nutrient absorption trends, and soil physicochemical properties, (2) to obtain carbon sequestration amount by calculating it based on the IPCC guidelines for greenhouse gas reduction, (3) to select the optimal application method of excessive biochar in *Raphanus raphanistrum* L. cultivation, considering both yield and carbon sequestration. These findings offer a strategy for carbon farming that simultaneously maximizes crop yield and carbon sequestration.

Materials and methods

Materials

The biochar used in this study was obtained from a thermal power plant that generates electricity using wood pellets as fuel, producing a solid byproduct during the process. This biochar was generated through a fast pyrolysis process at a high temperature of approximately 650 °C with a residence time of less than 1 s. The high-temperature biochar used in this experiment has been reported by Park et al. (2023) to be utilized as a fertilizer and agricultural material [23]. The biochar and soil properties are shown in Table 1.

Table 1 Physicochemical properties of soil and Biochar used in this study

Properties	Soil	Biochar
pH (1:5 H_2O)	7.10 ± 0.22[a)]	-
pH (1:5 $CaCl_2$)	-	9.02 ± 0.05
EC (dS m^{-1})	0.87 ± 0.13	25.1 ± 0.8
C (%)	-	72.6 ± 2.4
H/C	-	0.31 ± 0.04
O/C	-	0.07 ± 0.003
OM (g kg^{-1})	13.00 ± 0.10	-
TN (%)	0.025 ± 0.018	0.40 ± 0.03
TP (mg kg^{-1})	46.1 ± 1.1	1,913 ± 51
K (mg kg^{-1})	10,476 ± 765	125 ± 12
Ca (mg kg^{-1})	2,792 ± 272	19,466 ± 470
Mg (mg kg^{-1})	2,674 ± 562	4,116 ± 1
Na (mg kg^{-1})	600 ± 146	2,335 ± 271
Fe (mg kg^{-1})	-	1,025 ± 543
Mn (mg kg^{-1})	-	626 ± 51
Cu (mg kg^{-1})	-	32 ± 18
Zn (mg kg^{-1})	-	81 ± 5
SSA[b)] (m^2 g^{-1})	-	301 ± 5
PSD[c)] D_{10}[d)] (mm)	-	0.16
C_u[e)] D_{60}/D_{10} (mm)	-	4.375

[a)] Data are presented as mean values ± standard deviation ($n = 3$), [b)] SSA: Specific surface area, [c)] Particle Size Distribution, [d)] D_e: Effective Particle Diameter, [e)] C_u: Coefficient of Uniformity

Wild radish (*Raphanus raphanistrum* L.) is one of the major root vegetables cultivated in South Korea, along with garlic and onion. *Raphanus raphanistrum* L. was selected as a representative crop for this study.

Experimental methods

This study investigated the impact of excessive biochar application on *Raphanus raphanistrum* L. growth. The *Raphanus raphanistrum* L. cultivation experiment under excessive biochar application was conducted in a greenhouse located in Sacheon-si, Gyeongsangnam-do, South Korea (35°06'32.3"N, 128°07'09.5"E). The biochar treatments were divided into band application (B-BC) and broadcasting application (O-BC), each with a plot size of 100 cm × 100 cm, for a total area of 10,000 cm^2. Each treatment was replicated three times in a completely randomized design. All treatments were fertilized with NPK according to soil test-based fertilizer recommendations for *Raphanus raphanistrum* L. cultivation under greenhouse conditions. Basal fertilization applied NPK (t ha^{-1}) at 0.035-0.03-0.018, and topdressing applied NPK (t ha^{-1}) at 0.035-0-0.018. Biochar was used at 20 t ha, 10 times the conventional amount. In the B-BC treatment, furrows approximately 15 cm deep and 20 cm wide were dug in the center of the ridges, biochar was added, and then lightly covered with soil. In the O-BC treatment, biochar was spread on the soil surface and mixed evenly to a depth of 15 cm.

Raphanus raphanistrum L. seedlings were grown for a few weeks until they developed a couple of leaves, then transplanted in the field at a spacing of 30 cm × 40 cm and cultivated for 40 days. Crop growth surveys were conducted weekly (every 8 days) by the crop growth survey guidelines of the RDA [24]. After 40 days, the harvested *Raphanus raphanistrum* L. plants were analyzed for shoot length, leaf width, leaf count, fresh weight, dry weight, inorganic nutrient content (including N, P, K, Ca, Mg, etc.), and the yield was determined based on the fresh root weight to compare the effects of biochar treatment on both the *Raphanus raphanistrum* L. plants and soil conditions relative to the control.

The greenhouse gas reduction was calculated using the following equation presented in the IPCC (Intergovernmental Panel on Climate Change) guidelines [25]:

$$B_y = \sum_{p=1}^{n} \left(BC_{TOT_p} \text{ x } F_{c_p} \text{ x } F_{perm_p} \right) \text{ x } 3.664 \quad (1)$$

= total biochar-based CO_2 sequestration in year y (in tonnes CO_2-eq yr^{-1}).

n = the number of different production types of biochar.

p = biochar production type

BC_{TOT_p} = total dry mass of biochar applied in each production type p (tonnes yr^{-1})

F_{c_p} = fraction of biochar that is organic carbon for each production type p (tonnes C tonne^{-1} biochar dry matter)

F_{perm_p} = fraction of biochar carbon expected to remain sequestered after 100 years (tonnes sequestered C tonne^{-1} biochar C)

3.664 = molecular conversion factor from C to CO_2 (1 tonne of C = 3.664 tonnes of CO_2)

Analytical methods

Soil chemical properties were analyzed using the soil chemical analysis method by the RDA (2010) [26]. Soil pH and EC were measured in a 1:5 soil-to-distilled water using a pH meter (Orion 2 Star, Thermo Scientific, Singapore) and an EC meter (COM-100, HH Digital, USA), respectively. Organic matter was analyzed using the Tyurin method. TN was determined using the Kjeldahl method (K-365 BasicKjel, Buchi, Switzerland). Inorganic nutrients and heavy metals were prepared through acid digestion and measured using ICP-OES (iCAP Pro X Duo, Thermo Fisher Scientific, USA).

Harvested *Raphanus raphanistrum* L. was separated into shoot and root parts, and measurements were taken for shoot length, leaf width, leaf number, taproot length, taproot width, fresh weight, and dry weight. *Raphanus raphanistrum* L. yield was determined based on fresh weight at 40 days of cultivation. Total contents of N, P, K, Ca, Mg, and micronutrients in *Raphanus raphanistrum* L. tissues were analyzed according to the RDA's standard methods for soil and plant analysis (RDA, 2000) [27].

Biochar analysis was performed according to the standards for fertilizer quality inspection methods and sampling (RDA, 2022) [28].

Statistical analysis

The SPSS program (IBM SPSS Statistics 27) calculates means and standard deviations. To statistically analyze the differences between control and biochar treatments in *Raphanus raphanistrum* L. cultivation, analysis of variance (ANOVA) and Duncan's Multiple Range Test were conducted with statistical significance set at $p < 0.05$.

Results and discussion

The effect of excessive Biochar application on *Raphanus raphanistrum* L. Growth

Raphanus raphanistrum L. Growth characteristics

To evaluate the effects of excessive biochar application on the growth of root vegetables, the growth characteristics of *Raphanus raphanistrum* L. were investigated over 40 days under different fertilization methods with excessive amounts of biochar, as shown in Table 2.

Raphanus raphanistrum L. shoot length in the biochar treatments ranged from 15.9 to 17.0 cm after 8 days of growth, approximately 2.2–3.3 cm shorter than that in the control treatment (19.2 cm), likely due to initial growth inhibition. However, after 40 days of growth, shoot length in the O-BC treatment reached 30.6 cm, which was 1.7–2.0 cm longer than in the control and B-BC treatments. The taproot length showed a similar pattern to shoot length, while leaf and taproot width followed comparable trends. In contrast, the number of leaves remained relatively consistent across treatments throughout the growth period.

Overall, the O-BC treatment improved shoot elongation, leaf development, and taproot thickening compared to the other treatments. While B-BC underperformed in shoot length, leaf and taproot width compared to O-BC,

Table 2 Growth status of *Raphanus raphanistrum* L. over 40 days from transplanting to harvest

Items	Treatments	8	16	24	32	40
		At days after transplanting				
Shoot length (cm)	Control	19.2±1.5*b†	22.9±1.0a	28.1±1.6b	28.7±2.4a	28.9±2.3a
	B-BC	15.9±0.7a	23.2±1.6a	24.9±0.7a	27.2±1.7a	28.6±1.6a
	O-BC	17.0±2.5ab	26.1±0.7b	27.6±1.3b	28.3±0.95a	30.6±2.9a
Leaf width (cm)	Control	7.7±1.1b	11.4±1.1a	13.6±1.2a	15.1±2.5a	16.6±0.7a
	B-BC	6.4±0.4a	11.5±0.8a	12.1±0.8a	13.8±0.8a	16.1±0.6a
	O-BC	6.5±1.0a	12.4±1.1a	13.0±1.2a	15.9±1.1a	17.8±1.4b
Leaf number (ea)	Control	8.0±1.4a	13.2±0.8a	14.5±3.9a	14.8±0.8a	15.0±2.0a
	B-BC	8.4±0.5a	11.8±1.3a	14.6±0.5a	15.6±2.7a	16.4±3.2a
	O-BC	8.8±0.5a	12.0±1.0a	15.6±1.5a	16.4±2.5a	16.6±3.0a
Root[a)] length (cm)	Control	4.2±0.3b	NA[b)]	NA	NA	22.2±1.2a
	B-BC	3.6±0.1a	NA	NA	NA	22.6±1.1a
	O-BC	3.8±0.1a	NA	NA	NA	22.1±1.0a
Root width (cm)	Control	2.6±0.2b	NA	NA	NA	13.2±0.8a
	B-BC	2.0±0.2a	NA	NA	NA	12.7±0.7a
	O-BC	2.0±0.2a	NA	NA	NA	14.2±1.3b

*Data are presented as mean values ± standard deviation (n=8). †Means sharing the same letter are not significantly different according to Duncan's multiple range test ($p < 0.05$). [a)]The main root of the *Raphanus raphanistrum* L., excluding fine root structures. [b)]Not applicable:root data were not available for this period, as the *Raphanus raphanistrum* L. was not harvested for growth analysis

its growth patterns were similar to or slightly less favorable than the control.

In the study by Lee et al. (2024), which investigated the effects of excessive biochar application on lettuce growth, the B-BC treatment resulted in the best growth performance in lettuce cultivation, contrasting with the findings of the present study [16]. This difference is presumed to be due to the variation in shoot and root growth characteristics between leafy and root vegetables. For root vegetables such as *Raphanus raphanistrum* L., which require well-developed roots, the O-BC treatment appears to be more effective. These findings suggest that applying biochar at 10 times the conventional amount led to an improvement in crop growth compared to standard application levels.

Raphanus raphanistrum L. plants harvested 40 days after transplanting showed weights and yields as presented in Fig. 1. The total dry weight (shoot + root) was highest in the O-BC treatment (38.9 g), followed by B-BC (37.6 g), and the control (35.6 g) (Fig. 1A). The O-BC and B-BC treatments increased shoot dry weight by 9.1% and 13.6% compared to the control. Similarly, the O-BC and B-BC treatments increased root dry weight by 3.5% and 6.6%, and total dry weight of the whole plant rose by 5.4% and 9.0%, respectively. The fresh weight followed a similar trend to that of the dry biomass (Fig. 1B).

The O-BC led to the highest total crop yield (4.67 t ha^{-1}), followed by B-BC (4.51 t ha^{-1}) and the control (4.28 t ha^{-1}). The O-BC treatment yielded 6.61% compared to the control treatment (Fig. 1C). Lee et al. (2024) also reported that excessive biochar application increased yield by 10.58% compared with the control [16].

Biochar produced at higher temperatures exhibits a higher carbon content due to increased aromaticity compared to biochar produced at lower temperatures. Its larger surface area and more developed pore structure enhance its capacity to retain water and nutrients, while its stable carbon form contributes to improved carbon sequestration. Consequently, high-temperature biochar is considered more suitable for agricultural use due to its enhanced physicochemical properties [3–5, 23]. In contrast, low-temperature biochar has a lower carbon content but contains higher mineral nutrients than high-temperature biochar, making it suitable as an agricultural amendment. However, its specific surface area and pore structure are less developed, resulting in lower water retention and nutrient-holding capacity compared to high-temperature biochar.

Although low-temperature biochar is more energy-efficient to produce, the IPCC's greenhouse gas reduction estimates indicate that only about 65% ($Fperm_p$ in Eq. 1) of its carbon is expected to remain sequestered after 100 years. In contrast, approximately 89% ($Fperm_p$ in Eq. 1) of the carbon in high-temperature biochar is estimated to persist over the same period, demonstrating significantly greater long-term carbon stability and superior potential for enhancing crop productivity compared with low-temperature biochar [25].

The improved crop productivity observed under excessive biochar application is consistent with the results of Singh et al. (2022) and Mon & Ueno (2024), who reported increases of 10–57% at application amounts ranging from 10 to 80 t ha^{-1} [29]– [30]. On the other hand, Oh et al. (2017) reported a decline in productivity at high biochar amounts, linking the adverse effects to increased soil pH, reduced nutrient availability, and higher EC [15]. These contrasting findings highlight the significant role that soil conditions and biochar properties such as feedstock type, pyrolysis temperature, particle size, and carbon content play important roles in determining crop productivity.

In this study, O-BC treatment resulted in a 2.97% higher *Raphanus raphanistrum* L. yield than B-BC. In contrast, Lee et al. (2024) reported that under excessive biochar application in lettuce cultivation, B-BC produced the highest yield, outperforming O-BC by 102% [16]. This discrepancy may be due to the inherent differences between root and leafy vegetables, which also influence how each crop responds to fertilization methods and biochar placement, ultimately affecting nutrient uptake efficiency and biomass distribution.

Nutrient absorption characteristics

The concentrations and uptake of TN, TP, TK, and minerals in *Raphanus raphanistrum* L. plants 40 days after transplanting under excessive biochar application are presented in Fig. 2, and Tables 3-4.

The O-BC treatment resulted in a higher shoot TN concentration (1.60%) compared to the control (1.50%) and the B-BC treatment (1.28%). Root TN concentrations were similar across all treatments, ranging from 1.30% to 1.43% (Fig. 2A). Nitrogen promotes leafy growth [31], and the higher TN uptake observed in the O-BC treatment suggests improved nitrogen assimilation efficiency, likely due to the enhanced effectiveness of the broadcast application method, as reflected in the results shown in Table 2. For total phosphorus, the O-BC and B-BC treatments showed a lower TP concentration in the shoot compared to the control. All treatments resulted in TP concentrations in roots ranging from 6,900 to 7,276 mg kg^{-1} (Fig. 2C).

Phosphorus is essential for root development and crucial during early growth stages for proper root formation. Notably, phosphorus accumulation was greater in the roots than in the shoots under the O-BC treatment, suggesting enhanced P translocation or retention in root tissues associated with this method [32]. The O-BC and B-BC treatments showed higher TK concentrations both in the shoot and root compared to the control (Fig. 2E).

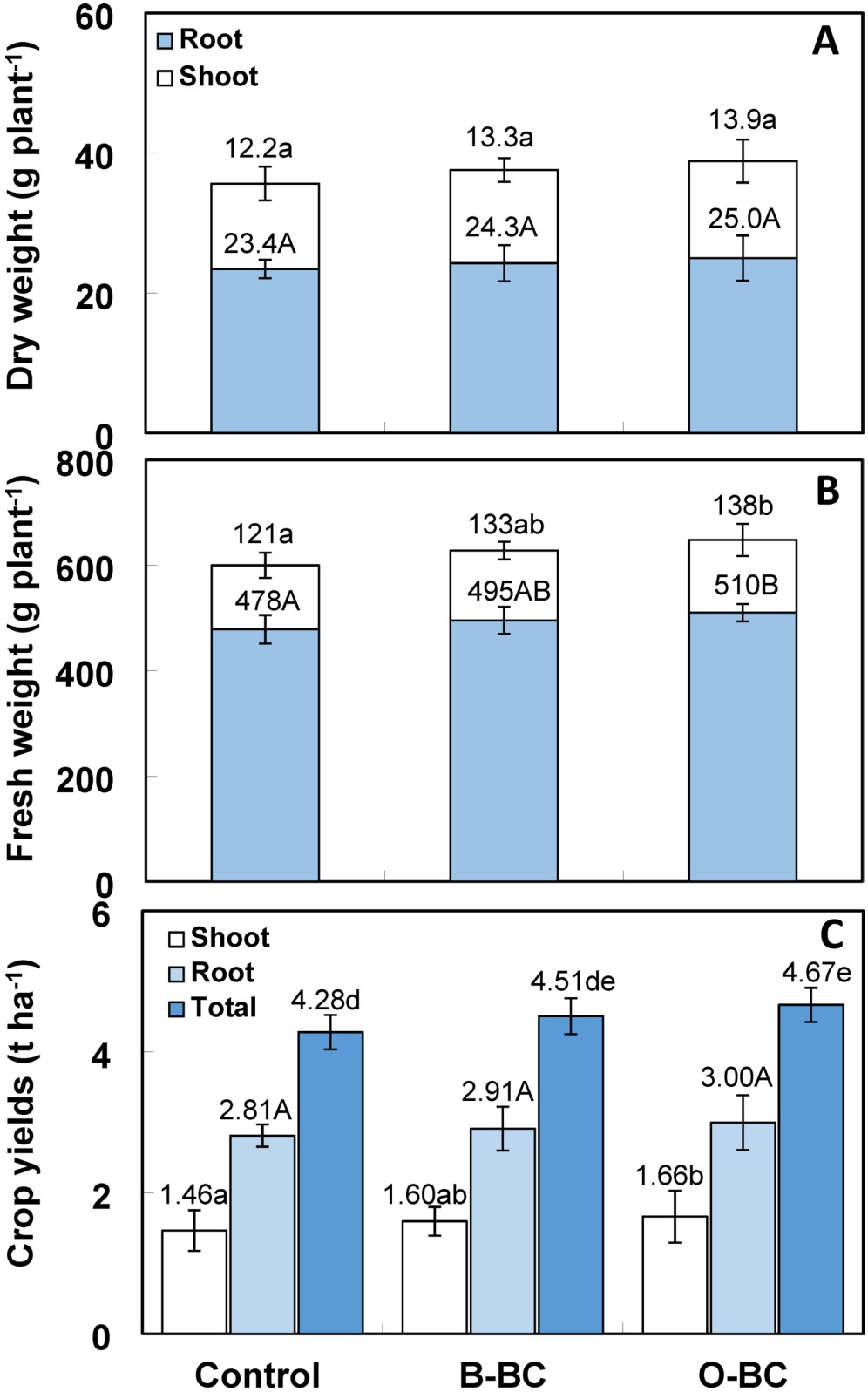


Fig. 1 Biomass (**A, B**) and yield (**C**) of *Raphanus raphanistrum* L. under different biochar treatments after harvest. Data are presented as mean values with error bars indicating standard deviation (n=8). One-way ANOVA followed by Duncan's multiple range test ($p < 0.05$) was performed for statistical analysis. Lowercase letters show significant differences in shoots; uppercase letters show differences in roots

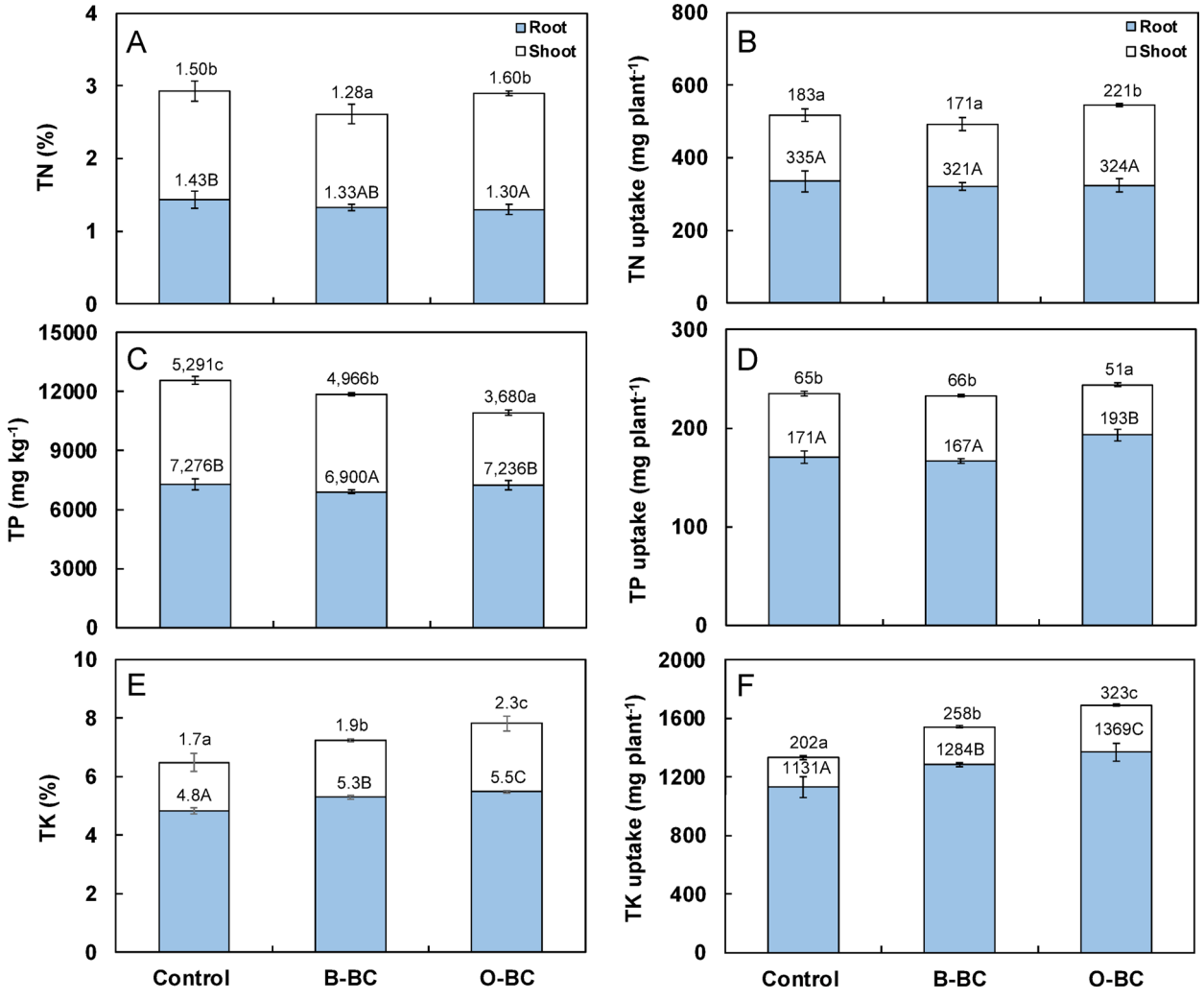


Fig. 2 The concentrations of TN (**A**), TP (**C**), and TK (**E**), and the uptake of TN (**B**), TP **(D)**, and TK (**F**) of *Raphanus raphanistrum* L. under different biochar treatments after harvest. Data are presented as mean values with error bars indicating standard deviation (n=5). One-way ANOVA followed by Duncan's multiple range test ($p < 0.05$) was performed for statistical analysis. Lowercase letters show significant differences in shoots; uppercase letters show differences in roots

Potassium plays a key role in disease resistance and promotes root thickening [33].

These concentration trends were reflected in TP and TK uptake in roots, which was significantly enhanced in the O-BC treatment, while TN uptake was similar among all the treatments. Uptake was calculated using nutrient concentrations and dry weight. Based on this, the O-BC treatment resulted in 5.05% higher TN uptake in the whole plant compared to the control and 9.75% higher than the B-BC treatment. The O-BC treatment showed the highest root uptake of both TP and TK, surpassing the other treatments by 11.7–13.6% and 6.2–17.4%, respectively (Fig. 2B, D, and F) ( ).

The shoot-to-root (S/R) ratios varied by treatment and nutrient type. For TN, the ratios were 0.68 in O-BC, 0.55 in the control, and 0.53 in B-BC. A different trend was seen for TP, with the lowest ratio in O-BC (0.26) and higher ratios in the control (0.38) and B-BC (0.40). In the case of TK, O-BC had the highest ratio (0.24), followed by B-BC (0.20) and the control (0.18) (Table 5).

Overall, all treatments showed a similar root TN pattern, while the O-BC treatment enhanced TP and TK availability in *Raphanus raphanistrum* L. roots. Biochar can improve nutrient availability by increasing soil pH from acidic soils, cation exchange capacity (CEC), total organic carbon (TOC), porosity, and microbial diversity. However, excessive changes, such as elevated pH, may reduce the availability of certain nutrients (e.g. NH_4^+) and cause micronutrient deficiencies. Studies have reported that high biochar levels can hinder plant establishment and nutrient uptake, ultimately reducing crop productivity [29, 34].

Table 3 Mineral content of *Raphanus raphanistrum* L. after harvest under different excessive Biochar treatments

Parts	Treatments	Ca	Mg	Na	B	Fe	Mn	Cu	Zn
		mg kg^{-1}							
Shoot	Control	22,346 ± 2,093*a†	6,549 ± 162b	3,135 ± 332b	36.8 ± 2.0b	161 ± 15.7a	277 ± 15.9b	ND	114 ± 9a
	B-BC	24,991 ± 7,125a	6,355 ± 103a	3,156 ± 141b	19.8 ± 5.9a	169 ± 17.8a	222 ± 5.75a	ND	139 ± 67a
	O-BC	20,748 ± 1,827a	6,561 ± 115b	2,757 ± 91a	17.2 ± 2.9a	208 ± 25.9b	208 ± 11.4a	ND	130 ± 2a
Root	Control	4,354 ± 171a	1,473 ± 75b	3,380 ± 258a	6.5 ± 5.8a	43.0 ± 17.8a	33.6 ± 5.85b	ND	76 ± 10b
	B-BC	4,294 ± 120a	1,362 ± 25a	3,291 ± 98a	10.4 ± 8.5a	37.5 ± 9.09a	22.6 ± 1.50a	ND	61 ± 3a
	O-BC	5,074 ± 124b	1,826 ± 57c	3,141 ± 83a	13.6 ± 12.3a	97.7 ± 33.3b	30.3 ± 1.13b	ND	88 ± 5c

* Data are presented as mean values ± standard deviation ($n = 5$). † The same letters are not significantly different (Duncan test, $p < 0.05$)

Table 4 Mineral uptake of *Raphanus raphanistrum* L. after harvest under different excessive Biochar treatments

Parts	Treatments	Ca	Mg	Na	B	Fe	Mn	Cu	Zn
		mg plant^{-1}							
Shoot	Control	301 ± 28*a†	88 ± 2b	42 ± 4b	0.49 ± 0.03b	2.16 ± 0.21a	3.73 ± 0.21b	ND	1.53 ± 0.12a
	B-BC	331 ± 94a	84 ± 1a	42 ± 2b	0.26 ± 0.08a	2.24 ± 0.24a	2.95 ± 0.08a	ND	1.84 ± 0.89a
	O-BC	279 ± 25a	88 ± 2b	37 ± 1a	0.23 ± 0.04a	2.79 ± 0.35b	2.79 ± 0.15a	ND	1.75 ± 0.03a
Root	Control	102 ± 4a	35 ± 2a	79 ± 6a	0.12 ± 0.14a	1.01 ± 0.42a	0.78 ± 0.14b	ND	1.78 ± 0.23b
	B-BC	104 ± 3a	33 ± 1a	80 ± 2a	0.25 ± 0.20a	0.91 ± 0.22a	0.54 ± 0.04a	ND	1.48 ± 0.08a
	O-BC	135 ± 3b	49 ± 1b	84 ± 2a	0.36 ± 0.33a	2.61 ± 0.89b	0.80 ± 0.03b	ND	2.36 ± 0.13c

* Data are presented as mean values ± standard deviation ($n = 5$). † The same letters are not significantly different (Duncan test, $p < 0.05$)

Soil physicochemical characteristics

Soil physicochemical properties after *Raphanus raphanistrum* L. harvest are shown in Table 5. Soil pH was slightly higher in the B-BC (7.85) and O-BC (7.70) treatments compared to the control (7.45). Electrical conductivity increased significantly with biochar application, particularly in the B-BC treatment (2.49 dS m^{-1}). Considering the pH and EC values, B-BC is likely to inhibit nutrient uptake [33, 34].

The OM, TN, Ca, and Mg contents of the soil exhibited similar trends, with no significant differences observed among the treatment conditions. Total P and K levels were slightly lower in the biochar treatments compared to the control, likely as a result of plant uptake. This nutrient uptake difference likely arises from the distinct soil mobility and physiological characteristics of these nutrients. The increase in soil pH may limit NH_4^+ by reducing plant nutrient absorption, and N in the soil may be less available to crops during the early growth stage due to its adsorption by biochar [34]. Similarly, P is highly sensitive to soil microbial activity and pH changes, and biochar may have influenced P fixation or reduced its availability [32, 34]. Potassium is relatively more mobile in the soil and can be more readily adsorbed and supplied through biochar application [33]. Therefore, the differences in nutrient uptake efficiency among N, P and K under biochar treatments can be attributed to their chemical properties and interactions within the soil environment.

These results indicate that excessive application of biochar altered the nutrient solubilization and utilization efficiency in the soil, particularly enhancing the uptake amounts of P and K, with this effect being especially pronounced under O-BC application [35, 36].

Growth trends across different plant components

The *Raphanus raphanistrum* L. growth trends in relation to biomass (dry weight, yield) and nutrient uptake (N, P, and K) under excessive biochar treatments with B-BC and O-BC are shown in Fig. 3.

The *Raphanus raphanistrum* L. growth patterns over 40 days after transplanting showed differences between the biochar treatments and the control. In the shoots, the biochar treatments showed slightly delayed growth compared to the control at the early stage (day 8), although the differences were not significant.

By the late growth stage (day 40), the biochar treatments generally promoted better growth than the control, except in P uptake. The uptake of N and P in the shoots

Table 5 Physicochemical properties of the soil after harvest under different excessive Biochar treatments

Treatments	pH	EC	OM	TN	TP	K	Ca	Mg	Na
	1:5 H_2O	dS m^{-1}	g kg^{-1}	%	mg kg^{-1}				
Control	7.45 ± 0.04*a†	1.63 ± 0.01a	26.4 ± 0.2a	0.051 ± 0.004a	497 ± 14b	9,548 ± 1,084a	5,499 ± 1,273a	2,236 ± 497a	381 ± 41c
B-BC	7.85 ± 0.03b	2.49 ± 0.02c	46.0 ± 0.4c	0.053 ± 0.001b	440 ± 43a	9,815 ± 826a	6,449 ± 1,110a	2,193 ± 674a	240 ± 30b
O-BC	7.70 ± 0.05b	2.26 ± 0.02b	37.8 ± 0.3b	0.051 ± 0.002a	390 ± 12a	10,280 ± 1,000a	5,267 ± 949a	2,102 ± 853a	168 ± 33a

* Data are presented as mean values ± standard deviation (n=3). †The same letters are not significantly different (Duncan test, p < 0.05)

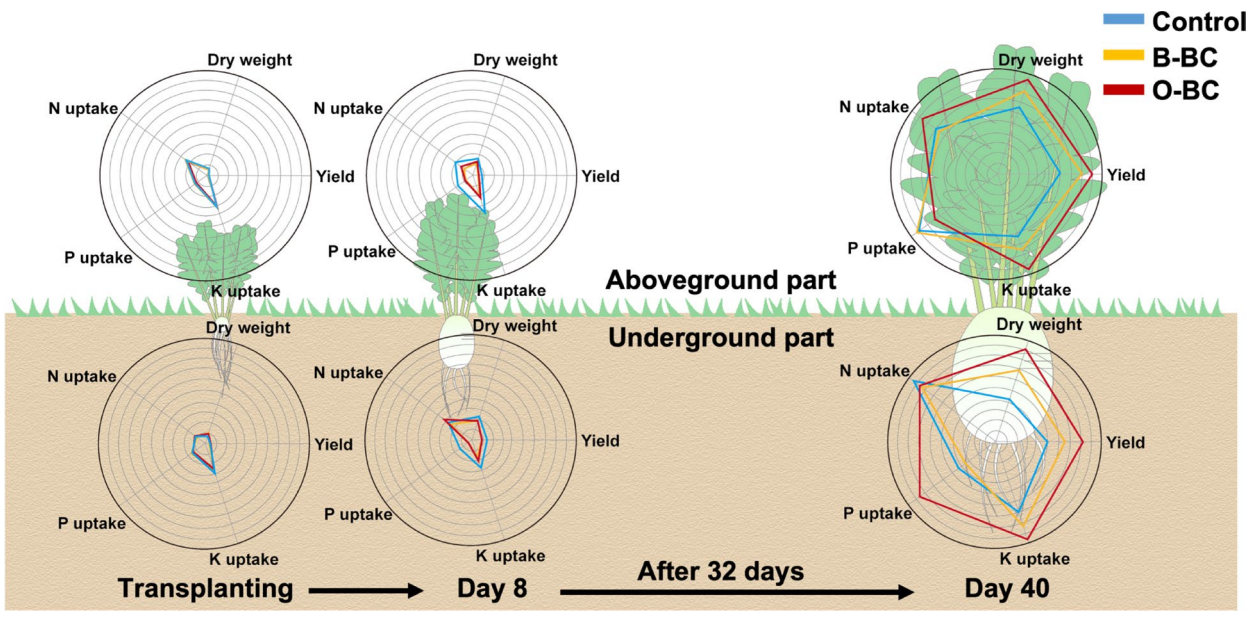


Fig. 3 Growth trends of five major components in shoots and roots of *Raphanus raphanistrum* L. under different biochar treatments during the cultivation period

showed opposite trends. The O-BC treatment resulted in higher N uptake, but lower P uptake compared to B-BC and the control, while B-BC and the control showed similar N and P uptake levels. The O-BC treatment demonstrated the enhanced *Raphanus raphanistrum* L. growth across the growth parameters most notably in biomass, and N and K uptake, indicating a positive effect on shoot growth and nutrient absorption. The control recorded the lowest values overall except P uptake in shoot, suggesting limited development and nutrient uptake without biochar amendment.

In the roots, the biochar treatments showed improved growth in terms of biomass and K uptake compared to the control, which followed the same pattern as in the shoots. Nitrogen uptake was similar across all treatments, while P uptake in the O-BC treatment was significantly higher than in both the B-BC and the control, which were similar to each other. The O-BC showed better root growth in biomass, P, and K uptake, indicating enhanced root productivity and nutrient assimilation. B-BC showed moderate improvements, particularly in biomass, and K uptake suggesting beneficial but milder effects. Interestingly, the control exhibited slightly higher nitrogen uptake than biochar treatments, highlighting an imbalance in nutrient acquisition and limited contribution to overall biomass.

By day 40 after transplanting, shoot and root biomass were higher in all biochar treatments compared to the control. Potassium uptake was also enhanced in both plant parts under biochar treatments. However, contrasting patterns were observed for N and P uptake. Phosphorus uptake in the O-BC treatment was lowest in the shoot but highest in the root, whereas nitrogen uptake was highest in the shoot but slightly lower in the root compared to the control and B-BC treatment.

Overall, at the initial growth stage (day 8), the excessive biochar treatments exhibited slightly reduced *Raphanus raphanistrum* L. growth compared to the control. However, by the final growth stage (day 40), all biochar treatments (band and broadcast applications) demonstrated improved *Raphanus raphanistrum* L. growth relative to the control. In particular, the broadcast application (O-BC) resulted in greater biomass content and enhanced K uptake in both shoot and root tissues, along with increased P uptake in the root. This result reveals that O-BC offers the most balanced and robust enhancement of *Raphanus raphanistrum* L. growth and nutrient acquisition across plant parts, while B-BC provides modest benefits.

Biochar treatments increased shoot dry weight and yield by 86.3–86.5%, compared to a 77.0% increase in the control from day 8 to day 40 after transplanting. Shoot N uptake followed a similar trend to biomass, with the control showing a 66.7% increase approximately 15% lower than the biochar treatments (80.8–81.3%). Shoot P uptake was highest in the B-BC treatment (87.5%), followed by O-BC (84.7%) and the control (81.3%). Biochar treatments also resulted in higher shoot K uptake (76.4–78.0%), while the control showed only a 45.1% increase.

Root dry weight and yield increased by 97.4–98.4% across all treatments. Nutrient uptake in roots showed a similar trend with N uptake increased by 99.0–99.3%, P by 98.5–99.1%, and K by 97.8–98.9% in all treatments.

Raphanus raphanistrum L. Growth and carbon sequestration effect

Greenhouse gas reduction from the agricultural byproduct biochar used in this experiment was calculated according to IPCC guidelines. Based on Eq. 1, with a carbon content of 72.6%, moisture content of 7.6%, and a 100-year residual carbon ratio of 89% for high-temperature biochar, the CO_2 reduction was estimated at 2.19 tons per ton of biochar. The greenhouse gas reduction in *Raphanus raphanistrum* L. cultivation soil with an excessive biochar application amount of 20 t ha^{-1} was calculated to be 43.75 t ha^{-1}, which is 10 times higher than the 4.38 t ha^{-1} reduction observed at the conventional biochar application amount of 2 t ha^{-1} [11–13].

Although excessive application of biochar may adversely affect crop growth or soil health [15], selecting appropriate application methods depending on crop type is important. Broadcasting application may simultaneously promote the growth of root vegetables such as *Raphanus raphanistrum* L. and enhance greenhouse gas mitigation.

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Author contributions
D.-C.S. and S.-R.L. designed the research; S.-R.L., J.-H.L., J.-S.R., J.-M.L., and S.-H.L. collected the data and performed the analysis; D.-C.S. and J.-H.P. provided overall inspiration, guiding the work and revising the final manuscript. All authors participated in the preparation of the manuscript, read, and approved the final version.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Shukla P, Skea J, Slade R, Khourdajie AA, van Diemen R, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S, Malley J (2022) In climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York. https://doi.org/10.1017/9781009157926.001
2. Kamyab H, SaberiKamarposhti M, Hashim H, Yusuf M (2024) Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review. Carbon Lett. https://doi.org/10.1007/s42823-023-00647-4
3. Zahra H, Payam G, Mohammad RK, Bijan Y (2023) Biomass-derived biochar and its application in agriculture. Fuel. https://doi.org/10.1016/j.fuel.2023.127701
4. Kurniawan TA, Othman MHD, Liang X, Goh HH, Gikas P, Chong KK, Chew KW (2023) Challenges and opportunities for biochar to promote circular economy and carbon neutrality. J Environ Manage. https://doi.org/10.1016/j.jenvman.2023.117429
5. Elkhlifi Z, Iftikhar J, Sarraf M, Ali B, Saleem MH, Ibranshahib I, Bispo MD, Meili L, Ercisli S, Torun Kayabasi E, Alemzadeh Ansari N, Hegedűsová A, Chen Z (2023) Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: a review. Sustainability. https://doi.org/10.3390/su15032527
6. Xia L, Cao L, Yang Y, Ti C, Liu Y, Smith P, Groenigen KJV, Lehmann J, Lal R, Butterbach-Bahl K, Kiese R, Zhuang M, Lu X, Yan X (2023) Integrated biochar solutions can achieve carbon-neutral staple crop production. Nat Food. https://doi.org/10.1038/s43016-023-00694-0
7. Guo C, Liu X, He X (2022) A global meta-analysis of crop yield and agricultural greenhouse gas emissions under nitrogen fertilizer application. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2022.154982
8. Kalu S, ulmala L, Zrim J, Peltokangas K, Tammeorg P, Rasa K, Kitzler B, Pihlatie M, Karhu K (2022) Potential of biochar to reduce greenhouse gas emissions and increase efficiency in boreal arable soils in the long-term. Front Environ Sci. https://doi.org/10.3389/fenvs.2022.914766
9. Cho HN, Shin M, Lee I, Ryoo H, Acharya BS, Park JH, Cheong YH, Cho JS, Kang SW (2023) Impact of biochar and compost amendment on corn yield and greenhouse gas emissions under waterlogged conditions. Appl Biol Chem. https://doi.org/10.1186/s13765-024-00868-9
10. Park JH, Lee SL, Lee JH, Rho JS, Lee JM, Kim SH, Kang SW, Seo DC (2023) Reduction of ammonia gas by microbial agent treatment in Chinese cabbage cultivation. Appl Biol Chem. https://doi.org/10.1186/s13765-023-00847-6
11. Kim SS, Rho JS, Lee JH, Choi AY, Lee SR, Park YJ, Park JH, Lee YH, Seo DC (2023) Salt removal and agricultural application of food waste-biochar. Korean J Environ Agric. https://doi.org/10.5338/KJEA.2023.42.2.19
12. Jeong TU, Lee JH, Rho JS, Lee DY, Lee JM, Park JH, Seo DC (2023) Application effect of rendering livestock carcass-based carbonized material in Chinese cabbage cultivation. Korean J Environ Agric. https://doi.org/10.5338/kjea.2023.42.3.21
13. Kang SW, Kim SH, Park JH, Seo DC, Cho JS (2017) Selection of optimal application condition of corn waste biochar for improvement of corn growth and soil fertility. Korean J Soil Sci Fertil. https://doi.org/10.7745/KJSSF.2017.50.5.452
14. Jeffery S, Verheijen FGA, van der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2011.08.015
15. Oh TK, Lee JH, Kim SH, Lee HC (2017) Effect of biochar application on growth of Chinese cabbage (*Brassica chinensis*). Korean J Agric Sci. https://doi.org/10.7744/kjoas.20170039
16. Lee SR, Lee JH, Rho JS, Park YJ, Lee JM, Park JH, Seo DC (2024) Effects of lettuce growth and carbon sequestration by different application methods with excessive amount of wood-based agricultural and forestry by-product biochar. Korean J Environ Agric. https://doi.org/10.5338/KJEA.2024.43.24
17. Bukhov NG, Bondar VV, Drozdova IS, Kara AN, Kotov AA, Maevskaya SN, Vasil'ev AA, Voevudskaya SY, Voronin PY, Mokronosov AT (1996) Development of storage roots in radish (*Raphanus sativus*) plants as affected by light quality. J Plant Physiol 149(3):405–412. https://doi.org/10.1016/S0176-1617(96)80141-6
18. SUOJALA T (2000) Growth of and partitioning between shoot and storage root of carrot in a Northern climate. Agric Food Sci. https://doi.org/10.23986/afsci.5646
19. White JM, Strandberg JO (1978) Early root growth of carrots in organic soil1. J Am Soc Hortic Sci. https://doi.org/10.21273/JASHS.103.3.344

20. Adhikari S, Anuragi H, Chandra K, Tarte SH, Dhaka SR, Jatav HS, Hingonia K (2023) Chapter six - Molecular basis of plant nutrient use efficiency - concepts and challenges for its improvement. In: Aftab T, Hakeem KR (eds) Sustainable plant nutrition, 1st edn. Academic, Massachusetts, pp 107–151
21. Ahmad R, Waraich EA, Ashraf MY, Ahmad S, Aziz T (2014) Does nitrogen fertilization enhance drought tolerance in sunflower? J Plant Nutr. https://doi.org/10.1080/01904167.2013.868480
22. Mengel K, Kirkby EA, Kosegarten H, Appel T (2001) Principles of plant nutrition, 5th edn. Kluwer Academic, Dordrecht, Netherlands
23. Park J, Wang JJ, Seo D (2023) Agronomic and environmental performance of bottom ash discharged from biomass-based thermal power plant. Sustain Chem Pharm. https://doi.org/10.1016/j.scp.2023.101097
24. Rural Development Administration (2012) Manual for crop growth survey. Rural Development Administration, Jeonju-si, Republic of Korea
25. Intergovernmental Panel on Climate Change (IPCC) (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC
26. Rural Development Administration, National Institute of Agricultural Sciences (2010) Methods of soil chemical analysis. National Institute of Agricultural Sciences, Wanju-gun, Republic of Korea
27. Rural Development Administration, National Institute of Agricultural Sciences (2000) Methods of soil and plant analysis. National Institute of Agricultural Sciences, Wanju-gun, Republic of Korea
28. Rural Development Administration (2022) Proposed partial amendment to the standards for fertilizer quality inspection methods and sampling (RDA notice No. 2022 – 205). Rural Development Administration, Jeonju-si, Republic of Korea
29. Singh H, Northup BK, Rice CW, Prasad PVV (2022) Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar. https://doi.org/10.1007/s42773-022-00138-1
30. War War Mon, &, Hideto U (2024) Short-term effect of the combined application of rice husk biochar and organic and inorganic fertilizers on radish growth and nitrogen use efficiency. Plants. https://doi.org/10.3390/plants13172376
31. Huang M, Yin X, Chen J, Cao F (2024) Biochar supplementation altered the expression of antioxidant proteins in rice leaf chloroplasts under high-temperature stress. Appl Biol Chem. https://doi.org/10.1186/s13765-024-00911-9
32. Ruan R, Wang Y (2024) Effects of biochar amendment on root growth and plant water status depend on maize genotypes. Agric Water Manage. https://doi.org/10.1016/j.agwat.2024.108688
33. Vélez-Bermúdez IC, Schmidt W (2023) Plant strategies to mine iron from alkaline substrates. Plant Soil. https://doi.org/10.1007/s11104-022-05746-1
34. Xiang L, Liu S, Ye S, Yang H, Song B, Qin F, Shen M, Tan C, Zeng G, Tan X (2021) Potential hazards of biochar: the negative environmental impacts of biochar applications. J Hazard Mater. https://doi.org/10.1016/j.jhazmat.2021.126611
35. Park DG, Jeong HC, Jang EB, Lee JM, Lee HS, Park HR, Lee SI, Oh TK (2024) Effect of rice hull biochar treatment on net ecosystem carbon budget and greenhouse gas emissions in Chinese cabbage cultivation on infertile soil. Appl Biol Chem. https://doi.org/10.1186/s13765-024-00903-9
36. Lee YN, Kim SS, Lee DW, Shim JH, Jeon SH, Roh AS, Kwon SI, Seo DC, Kim SH (2024) Correction to: Characterization and application of biochar derived from greenhouse crop by-products for soil improvement and crop productivity in South Korea. Appl Biol Chem. https://doi.org/10.1186/s13765-024-00968-6

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