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RESEARCH ARTICLE

Synergy and comprehensive evaluation of biochar-based biogas residue fertilizer for enhancing yield and quality of greenhouse cucumber

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ABSTRACT

The application of engineered organic amendments is crucial for advancing sustainable greenhouse vegetable production. This study evaluated the effects of a biochar-based biogas residue fertilizer (BRC) on cucumber (*Cucumis sativus* L.) in a greenhouse system. Eight fertilization treatments were applied, including different N levels and combinations with chemical fertilizers. These included a control group with no fertilization (CK), conventional chemical fertilizer (CF), biogas residue from cow manure (BR), biochar-based biogas residue without chemical fertilizer (BRC), biogas residue mixed with chemical fertilizer (CB), and biochar-based biogas residue combined with chemical fertilizer (CBC). The results indicated that BRC significantly enhanced cucumber physiological performance: It increased the average growth rate by 21.95% compared to the unamended control and improved root activity by up to 46.34% relative to CF. Although the highest cucumber yield was achieved under sole high-rate biogas residue (BR-34), BRC treatments increased yield relative to conventional chemical fertilization (CF-34) and markedly improved N use efficiency by 109.27%. Notably, BRC improved fruit quality by elevating vitamin C and soluble protein contents while significantly reducing nitrate accumulation. A fuzzy mathematics-based comprehensive evaluation confirmed that CBC-34 (combined BRC and mineral fertilizer treatment) achieved the highest overall fruit quality score of 0.73. The synergistic effect between biochar and biogas residue likely moderated nutrient release and improved rhizosphere conditions. This work reveals that sole BRC application delivers outstanding N retention capacity, whereas CBC-34 balances nutrient supply, crop growth and fruit quality; thus CBC-34 is the optimal integrated fertilization regime for sustainable greenhouse cucumber production.

Key words: Biochar-based fertilizer, comprehensive evaluation, fruit quality, greenhouse cucumber production, nitrogen use efficiency, synergistic effects.

INTRODUCTION

The protected cultivation of cucumber (*Cucumis sativus* L.) plays a vital role in meeting the global demand for fresh vegetables. To achieve high productivity, greenhouse systems have long depended on intensive N fertilization. However, excessive and imbalanced application of synthetic N fertilizers is associated with serious environmental and agronomic issues, including soil acidification, nitrate leaching into groundwater, and emissions of nitrous oxide—a potent greenhouse gas (Menegat et al., 2021; Hale et al., 2023). Moreover, high nitrate accumulation in edible plant parts poses potential health risks to consumers (Cheraghi et al., 2025).

Consequently, there is an urgent need to develop fertilization strategies that can maintain yield while enhancing N use efficiency (NUE) and improving the nutritional quality and safety of vegetables (Jia et al., 2021; Wang et al., 2021).

In recent years, recycling organic agricultural wastes into soil amendments has gained considerable attention as a sustainable alternative. Biogas residue (BR), a nutrient-rich byproduct from the anaerobic digestion of livestock manure, has been recognized for its potential to improve soil fertility, supply organic matter, and stimulate microbial activity (Tsachidou et al., 2021; Song et al., 2023). Similarly, biochar (BC), produced from the pyrolysis of biomass under limited oxygen, has been widely reported to enhance soil water retention, increase cation exchange capacity, reduce nutrient leaching, and promote C sequestration (Waheed et al., 2025). Studies have shown that the individual application of BR or BC can positively influence crop growth and soil properties (Martínez-Gómez et al., 2022; Zhang et al., 2024).

Despite these benefits, the sole use of BR or BC presents certain limitations. The BR decomposes relatively quickly, which may lead to asynchronous nutrient release and increase the risk of nutrient loss. The BC, although effective in improving soil physical and chemical properties, often has a low nutrient content and may induce short-term N immobilization, potentially limiting early crop growth (Pulliam et al., 2025). These drawbacks highlight the need for integrated amendments that can synchronize nutrient supply with plant demand. The concept of combining BC with organic nutrient sources to develop “engineered” or “designer” biochar-based fertilizers has recently emerged as a promising approach to achieve controlled nutrient release and enhanced fertilizer efficiency (Wang et al., 2022; Palansooriya et al., 2025; Wihardjaka et al., 2025). However, systematic research evaluating the performance of such composites, particularly for high-input greenhouse vegetable production systems, remains limited.

Furthermore, most existing studies have focused primarily on the effects of amendments on soil properties or final yield, while comprehensive investigations linking amendment application to crop physiological processes—such as root development, nutrient uptake dynamics, and photosynthetic efficiency—are scarce. A deeper understanding of these physiological mechanisms is essential to explain how integrated amendments influence crop performance. Additionally, evaluations of vegetable quality in response to fertilization are often fragmented, focusing on single nutritional or safety indicators. An integrated assessment that simultaneously considers multiple quality attributes is critical for a holistic judgment but is rarely conducted using robust, multi-criteria decision-making models.

To address these research gaps, this study developed a novel biochar-based biogas residue fertilizer (BRC) and systematically evaluated its effects on greenhouse cucumber (*Cucumis sativus* L.) We assessed whether the co-application of BC and BR could synergistically improve rhizosphere conditions to enhance root activity, nutrient uptake, and photosynthetic performance, thereby increasing cucumber yield and NUE compared to conventional chemical fertilizer. Furthermore, we examined its potential to improve fruit quality by elevating beneficial nutritional components while reducing nitrate accumulation. Eight fertilization treatments incorporating different N levels and combination strategies were conducted. A range of growth and physiological parameters were measured, yield and NUE were determined, and key fruit quality traits were analyzed. Additionally, a fuzzy mathematics membership function model was employed to integrate multiple quality indicators into a comprehensive score, providing a nuanced and holistic evaluation. This study elucidates the mechanisms through which an engineered biochar-organic amendment enhances cucumber production and offers a practical, sustainable fertilization strategy for high-quality greenhouse vegetable cultivation.

MATERIALS AND METHODS

The cucumber (*Cucumis sativus* L.) ‘Jinyou No. 3’ was used throughout the experiment, obtained from the Seed Industry Science and Technology Center in Yangling, Shaanxi Province, China. Nitrogen, P, and K were supplied in the form of urea (46% N), superphosphate (≥ 16% P_2O_5), and potassium sulfate (≥ 51% K_2O), respectively. Biogas residue (BR) was collected from the anaerobic digestion of cow manure at the Biomass Energy Innovation Base of Northwest A&F University. Biochar (BC) was produced through the pyrolysis of fruit tree branches at 550 °C for 6 h. The experimental soil was classified as a typical Lou soil (USDA taxonomy: Fine-loamy, mixed, active, thermic Typic Haplustalfs) collected from the Guanzhong region of Shaanxi Province.

Experimental design

The experiment was carried out in a plastic greenhouse at the Biomass Energy Innovation Base of Northwest A&F University. The design comprised eight treatments: No fertilizer blank control (CK); single conventional chemical fertilizer, 34 g N m^{-2} (CF-34); sole cow dung biogas residue applied at 17 and 34 g N m^{-2}, respectively (BR-17, BR-34); sole biochar-based biogas residue with chemical fertilizer at 17 and 34 g N m^{-2}, respectively (BRC-17, BRC-34); biogas residue mixed with chemical fertilizer, 34 g N m^{-2} (CB-34); biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2} (CBC-34). The detailed fertilization scheme for each treatment is provided in Table 1. Notably, BRC-34 and CBC-34 had identical total N input (34 g N m^{-2}) and biochar application rate (3 kg·m^{-2}), while their core distinction lay in the dosage of cow dung biogas residue: BRC-34 received 14 kg·m^{-2} cow dung biogas residue without additional chemical fertilizer, whereas CBC-34 only applied 7 kg·m^{-2} biogas residue combined with mineral N-P-K fertilizers.

Table 1. Fertilization application rates of all eight experimental treatments. CK: No fertilizer blank control; CF-34: single conventional chemical fertilizer, 34 g N m^{-2}; BR-17, BR-34: sole cow dung biogas applied at 17 and 34 g N m^{-2}; BRC-17, BRC-34: sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2}; CB-34: biogas residue mixed with chemical fertilizer, 34 g N m^{-2}; CBC-34: biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2}. BRC-34 and CBC-34 have identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) dosage; BRC-34 contains 14 kg m^{-2} cow dung biogas residue without mineral fertilizer, while CBC-34 only uses 7 kg m^{-2} biogas residue supplemented with N-P-K chemical fertilizers. All rates are calculated based on experimental plot area.

Treatment Group	N application rate	Biochar dosage	Cow dung biogas residue dosage	N fertilizer rate	P fertilizer rate	K fertilizer rate
	g N m^{-2}	kg m^{-2}	kg m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}
CK	0	0	0	0	0	0
CF-34	34	0	0	74	788	1149
BR-17	17	0	7	0	0	0
BRC-17	17	3	7	0	0	0
BR-34	34	0	14	0	0	0
BRC-34	34	3	14	0	0	0
CB-34	34	0	7	37	394	575
CBC-34	34	3	7	37	394	575

Growth and physiological parameters

Beginning at 28 d after transplanting (DAT), when cucumbers entered the rapid growth phase, plant height and leaf number were recorded at 5 d intervals until 53 DAT. At 30 and 60 DAT, stem diameter was measured for each plant. The area and net photosynthetic rate of the fully expanded functional leaf (fourth leaf from the apex) were also determined at these two time points. Net photosynthetic rate was measured between 10:00 and 14:00 h using a portable photosynthesis system (YX-1105, Beijing Yaxinliyi Science and Technology, Beijing, China).

Root activity

At the end of the fruiting stage, roots were carefully collected, washed, and separated from the shoots. Approximately 0.5 g fresh root samples were placed in flasks containing 5 mL 4% triphenyltetrazolium chloride (TTC) solution and 5 mL phosphate buffer. The samples were incubated in darkness at 37 °C for 1 h to allow dehydrogenase extraction. The reaction was terminated by adding 2 mL 1 mol L^{-1} sulfuric acid. The absorbance was measured at 485 nm using a UV-2310 II spectrophotometer (Techcomp Scientific Instrument, Shanghai, China).

Yield determination and fruit quality analysis

After the plants entered the fruiting stage, cucumbers were harvested daily from each plot. The total fresh weight per plot was recorded and used to calculate the average yield for each treatment.

Soluble sugar content was determined using the anthrone-sulfuric acid method. Briefly, 0.5 g fresh cucumber pulp was homogenized with 1 mL distilled water, diluted to 10 mL, and boiled for 10 min in a water bath. After cooling and filtration, the extract was brought to 100 mL. Then 1 mL solution was mixed with 0.5 mL anthrone reagent and 1 mL water, followed by the careful addition of 5 mL concentrated sulfuric acid. The mixture was heated in a boiling water bath for 10 min, cooled, and the absorbance was read at 620 nm.

Soluble protein was quantified according to the Coomassie brilliant blue G-250 method. A 1 g fresh sample was ground with 1 mL water, rinsed with 2 mL water, and centrifuged at 3500 rpm for 20 min. The supernatant (1 mL) was reacted with 5 mL Coomassie brilliant blue G-250 reagent for 5 min, and absorbance was measured at 595 nm.

Vitamin C content was determined using the phosphomolybdate colorimetric method. Briefly, 2 g fresh cucumber pulp was homogenized with 5 mL oxalic acid-EDTA solution. The homogenate was transferred into a volumetric flask, and the mortar was rinsed with additional oxalic acid-EDTA solution. After centrifugation at 3000 rpm for 10 min, 1 mL supernatant was mixed with 1 mL metaphosphoric-acetic acid solution, 2 mL 5% sulfuric acid, and 4 mL ammonium molybdate solution. The mixture was then diluted to 50 mL with distilled water, allowed to stand for 15 min, and the absorbance was measured at 705 nm.

Nitrate concentration of fresh cucumber pulp was determined as follows. Briefly, 0.5 g fresh cucumber pulp was ground with 1 mL distilled water to form a slurry, which was then transferred into a 100 mL volumetric flask with 30 mL water. Subsequently, 5 mL ammonia buffer solution, 30 mL distilled water, and 0.5 g activated carbon were added. The mixture was shaken thoroughly and allowed to stand for 20 min. Then, 1 mL potassium ferricyanide solution and 2 mL zinc sulfate solution were added, mixed well, and diluted to the mark with distilled water. After standing for 5 min, the solution was filtered, and the absorbance was measured at 219 nm.

Nitrogen use efficiency (NUE)

Because two N levels (17 and 34 g N m^{-2}) were used, direct yield comparison across levels was not appropriate. Therefore, N use efficiency (NUE) was calculated for each treatment as the ratio of fruit yield to applied N:

$$\mathrm{NUE} = (\mathrm{Y} - \mathrm{Y_0})/\mathrm{F_N} \quad (1)$$

where Y is the cucumber yield of a given treatment (kg m^{-2}), Y_0 is the yield of the control (CK, no N applied), and F_N is the N application rate of the treatment (g m^{-2}).

Comprehensive quality evaluation

A fuzzy mathematics membership function approach was employed to score the quality indices: Soluble sugar, soluble protein, vitamin C, and nitrate. For soluble sugar, soluble protein, and vitamin C (beneficial components), higher values correspond to better quality. The membership function was calculated as:

$$\mathrm{x_i} = (\mathrm{x} - \mathrm{x_{min}})/(\mathrm{x_{max}} - \mathrm{x_{min}}) \quad (2)$$

For nitrate (a safety indicator, where lower values are preferred), the function was:

$$\mathrm{x_i} = 1 - (\mathrm{x} - \mathrm{x_{min}})/(\mathrm{x_{max}} - \mathrm{x_{min}}) \quad (3)$$

where x_i is the observed value for a given treatment, and x_{min} and x_{max} are the minimum and maximum values across all treatments, respectively.

The weight of each quality indicator was determined using the analytic hierarchy process (AHP) with a 5 points scale. Vitamin C was assigned the highest score (5), followed by nitrate (3), soluble sugar (2), and soluble protein (1). The comparison matrix and calculated weights are shown in Table 2. The comprehensive quality score X for each fertilizer treatment was computed as:

$$\mathrm{X} = \sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{w_i} \cdot \mathrm{x_i} \quad (4)$$

where w_i is the weight of the i^{th} indicator, x_i is its membership value, and *n* = 4 in this study.

Table 2. Judgment matrix and weight coefficients of four cucumber fruit quality indicators via analytic hierarchy process (AHP).

Index	Nutritional ingredient				Weight
	Soluble protein	Soluble sugar	Vitamin C	Nitrate	
Soluble protein	1	0.5	0.2	1/3	9.091%
Soluble sugar	2	1	0.4	2/3	18.182%
Vitamin C	5	2.5	1	5/3	45.455%
Nitrate	3	1.5	0.6	1	27.273%

RESULTS AND DISCUSSION

Effects of biochar-based biogas residue fertilizer on physiological characteristics of cucumber

The application of biochar-based biogas residue fertilizer (BRC) elicited a multifaceted improvement in the physiological performance of greenhouse cucumber. The BRC application promoted cucumber vegetative growth, stem diameter, as well as leaf area and photosynthetic capacity in the late growth stage. Among all relevant treatments, BRC combined with chemical fertilizer (CBC-34) exhibited superior growth performance. Notably, BRC with chemical fertilizer (BRC-34) and CBC-34 had identical total N input (34 g N m^{-2}) and biochar application rate (3 kg·m^{-2}), while their core distinction lay in the dosage of cow dung biogas residue: BRC-34 received 14 kg·m^{-2} cow dung biogas residue without additional chemical fertilizer, whereas CBC-34 only applied 7 kg·m^{-2} biogas residue combined with mineral N-P-K fertilizers. Most notably, BRC treatments significantly enhanced root activity, especially under moderate N supply, indicating a substantial improvement in nutrient- and water-acquisition efficiency.

Effect of biochar-based biogas residue fertilizer on cucumber growth rate

The dynamics of cucumber plant height from 28 to 53 d after transplanting (DAT) are shown in Figure 1. Throughout this period, BRC treatments (BRC-17 and BRC-34) consistently produced taller plants than their corresponding biogas-residue-only counterparts (BR-17 and BR-34), with BRC-34 exhibiting the highest mean plant height overall. During the first 33 DAT, plants in the CBC-34 (combined BRC and chemical fertilizer) treatment were relatively short, exceeding only the unamended control (CK). After 33 DAT; however, plant height in CBC-34 increased rapidly, surpassing that of BR-17 and BR-34 by 48 DAT and reaching a level comparable to BRC-34 by 53 DAT. A similar delayed-growth pattern was observed in the conventional fertilizer treatment (CF-34).

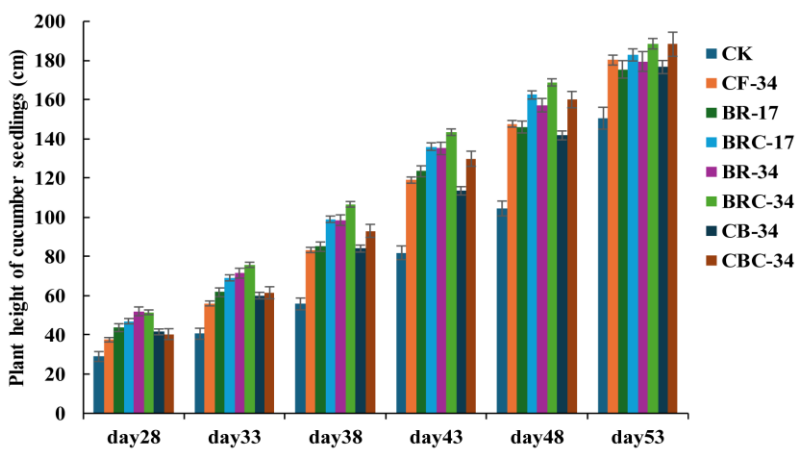

Figure 1. Dynamic changes in cucumber plant height from 28 to 53 d after transplanting (DAT). Values are mean ± standard deviation. Eight fertilization treatments: No fertilizer blank control (CK); single conventional chemical fertilizer, 34 g N m^{-2} (CF-34); (sole cow dung biogas residue applied at 17 and 34 g N m^{-2} (BR-17, BR-34 respectively); sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2} (BRC-17, BRC-34 respectively); biogas residue mixed with chemical fertilizer, 34 g N m^{-2} (CB-34); biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2} (CBC-34). BRC-34 and CBC-34 received identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) rates; the key difference is cow dung biogas dosage: BRC-34 received 14 kg m^{-2} biogas residue with no mineral fertilizer, while CBC-34 only used 7 kg m^{-2} biogas residue combined with N-P-K chemical fertilizers.

Plant growth rate is governed primarily by the availability of soil nutrients and the efficiency of nutrient uptake. In this experiment, the fertilizer regime significantly influenced cucumber growth, whereas the level of N application (17 *vs*. 34 g N m^{-2}) did not produce a significant difference, suggesting that the lower N supply was sufficient to support vegetative growth. Nevertheless, the reproductive phase also demands substantial nutrient uptake, indicating that 17 g N m^{-2} may not meet the crop's complete nutritional requirement. The initially slower growth in CF-34 and CBC-34 is likely attributable to the time required for urea hydrolysis. Urease activity was relatively low in these treatments, delaying the release of plant-available N and thus temporarily restraining early growth. The mean growth rate calculated over the first 53 DAT (Table 3) was highest in BRC-34 and CBC-34, and lowest in CK. Compared with CK, BRC-34 and CBC-34 increased the average growth rate by 21.95%; compared with CF-34, the increase was 5.13%. The overall ranking of growth rates was: BRC-34 = CBC-34 > BRC-17 > CB-34 > CF-34 > BR-34 > BR-17 > CK. Notably, BRC-34, CBC-34, and BRC-17 showed growth-rate enhancements of 5.47%, 7.19%, and 4.62% relative to their respective controls (BR-34, CB-34, and BR-17).

Table 3. Average daily growth rate of cucumber seedlings from 28 to 53 d after transplanting. CK: No fertilizer blank control; CF-34: single conventional chemical fertilizer, 34 g N m^{-2}; BR-17, BR-34: sole cow dung biogas applied at 17 and 34 g N m^{-2}; BRC-17, BRC-34: sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2}; CB-34: biogas residue mixed with chemical fertilizer, 34 g N m^{-2}; CBC-34: biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2}. BRC-34 and CBC-34 have identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) dosage; BRC-34 contains 14 kg m^{-2} cow dung biogas residue without mineral fertilizer, while CBC-34 only uses 7 kg m^{-2} biogas residue supplemented with N-P-K chemical fertilizers.

Treatment Group	CK	CF-34	BR-17	BRC-17	BR-34	BRC-34	CB-34	CBC-34
Growth rate	2.56	3.12	3.03	3.17	3.11	3.28	3.06	3.28

When soil nutrients are not limiting, the efficiency of root acquisition becomes the decisive factor for growth. Previous studies have demonstrated that sole applications of biochar (BC) or biogas residue (BR) can improve soil physical-chemical properties (e.g., pH, electrical conductivity, bulk density), thereby enhancing root absorption capacity and promoting plant development (Chang et al., 2021). In the present study, the significantly higher growth rates observed in the BRC treatments underscore a synergistic soil-ameliorating effect when BC and BR are applied together. This synergy likely improves nutrient retention and root-zone conditions, leading to more sustained nutrient uptake. Our results align with earlier findings that BC, when combined with organic or mineral fertilizers, can exert a positive interactive effect on crop growth (Hu et al., 2024). The delayed but strong growth response in CBC-34 further highlights the role of balanced nutrient release—where BC mitigates early N leaching while BR supplies organic nutrients—thereby supporting prolonged vegetative growth.

Effect of biochar-based biogas residue fertilizer on cucumber morphological structure

As the primary site of photosynthesis, leaf development, quantified by leaf number and area, directly influences cucumber yield potential. Therefore, we assessed these morphological parameters at 30 and 60 DAT. The results are summarized in Table 4. At 30 DAT, nonsignificant differences in leaf number were observed among the fertilizer treatments. By 60 DAT, the lowest leaf counts were recorded in the CK, BR-17, and BRC-17 groups, while nonsignificant differences existed among the remaining treatments. Leaf number generally increased with higher fertilizer application, with the BR-34 treatment showing the highest value, 51.80% greater than CK. Compared with their respective controls (BR-34, BR-17, and CB-34), the BRC-34, BRC-17, and CBC-34 treatments did not exhibit significant differences in leaf number, indicating that the amendment with biochar-based biogas residue had no pronounced effect on this trait.

Table 4. Leaf number and functional leaf area of cucumber at 30 and 60 d after transplanting. Values are mean ± standard deviation. Different lowercase letters in the same column represent significant differences ($p < 0.05$). CK: No fertilizer blank control; CF-34: single conventional chemical fertilizer, 34 g N m^{-2}; BR-17, BR-34: sole cow dung biogas applied at 17 and 34 g N m^{-2}; BRC-17, BRC-34: sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2}; CB-34: biogas residue mixed with chemical fertilizer, 34 g N m^{-2}; CBC-34: biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2}. BRC-34 and CBC-34 have identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) dosage; BRC-34 contains 14 kg m^{-2} cow dung biogas residue without mineral fertilizer, while CBC-34 only uses 7 kg m^{-2} biogas residue supplemented with N-P-K chemical fertilizers.

Treatment group	Number of leaves		Leaf area	
	30 d	60 d	30 d	60 d
	Nr		cm^2	
CK	6.57 ± 1.55	15.29 ± 1.31^c	63.77 ± 3.27^c	211.37 ± 6.37^d
CF-34	7.46 ± 1.61	22.12 ± 2.19^a	73.57 ± 5.44^b	256.73 ± 8.44^{ab}
BR-17	7.86 ± 1.75	18.79 ± 1.26^b	80.69 ± 2.77^a	254.28 ± 4.32^b
BRC-17	8.43 ± 1.28	18.14 ± 0.96^b	71.98 ± 3.98^b	252.33 ± 4.77^b
BR-34	8.29 ± 1.10	23.21 ± 1.53^a	82.33 ± 4.63^a	262.67 ± 3.68^a
BRC-34	9.29 ± 1.87	22.86 ± 1.53^a	80.62 ± 2.43^a	266.41 ± 2.97^a
CB-34	7.67 ± 1.64	21.62 ± 1.57^a	74.05 ± 4.66^b	257.63 ± 4.36^{ab}
CBC-34	7.64 ± 1.90	21.36 ± 1.69^{ab}	73.93 ± 5.85^b	269.17 ± 5.21^a

With respect to leaf area, at 30 DAT the functional leaf area was notably lower in the BRC-17, CF-34, CB-34, and CBC-34 treatments. Specifically, the leaf area in BRC-17 was 10.79% smaller than that in BR-17. By 60 DAT, however, nonsignificant differences in functional leaf area were detected among treatments under the same N level. The suppressive effect of low-level biochar-based fertilizer on early leaf expansion may be attributed to the adsorption of readily available N by BC, which temporarily reduces soil N availability during the initial growth stage (Chamoli et al., 2025). Similarly, the smaller leaf area in CF-34, CB-34, and CBC-34 could result from reduced urease activity following chemical fertilizer application, which slows the hydrolysis of urea into plant-available N and thus restrains leaf development (Sigurdarson et al., 2018).

Stem diameter and net photosynthetic rate were measured at 30 and 60 DAT (Table 5). During the first 30 DAT, fertilizer treatments had nonsignificant effect on stem diameter. Between 30 and 60 DAT, stem diameter increased significantly in the BRC-17 treatment compared with its biogas-residue-only counterpart (BR-17), whereas no such effect was observed for BRC-34 relative to BR-34. Notably, at the same N level, the conventional fertilizer treatment (CF-34) produced significantly thinner stems than the other treatments, which may impede the efficiency of internal nutrient and water transport.

Net photosynthetic rate showed no marked variation among treatments at 30 DAT, except for the lower value in CK. By 60 DAT, the highest photosynthetic rate was observed in CBC-34, exceeding those in BRC-34 and CF-34 by 21.94% and 11.30%, respectively. In contrast, photosynthesis in BRC-17 was significantly suppressed, showing a 16.43% reduction relative to BR-17, while nonsignificant differences were found between BR-34 and BRC-34 or between CB-34 and CBC-34. Chlorophyll synthesis, which largely governs leaf photosynthetic capacity, depends critically on Mg and N availability (Li et al., 2021). The adsorption of soil nutrients (including P and N) by BC may reduce their short-term accessibility (Wang et al., 2025), particularly under low application rates, thereby limiting chlorophyll formation and depressing photosynthesis in treatments such as BRC-17.

Table 5. Stem diameter and net photosynthetic rate of cucumber leaves at 30 and 60 d after transplanting. Values are mean ± standard deviation. Different lowercase letters in the same column represent significant differences ($p < 0.05$). CK: No fertilizer blank control; CF-34: single conventional chemical fertilizer, 34 g N m^{-2}; BR-17, BR-34: sole cow dung biogas applied at 17 and 34 g N m^{-2}; BRC-17, BRC-34: sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2}; CB-34: biogas residue mixed with chemical fertilizer, 34 g N m^{-2}; CBC-34: biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2}. BRC-34 and CBC-34 have identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) dosage; BRC-34 contains 14 kg m^{-2} cow dung biogas residue without mineral fertilizer, while CBC-34 only uses 7 kg m^{-2} biogas residue supplemented with N-P-K chemical fertilizers.

Treatment group	Stem diameter		Net photosynthetic rate	
	30 d	60 d	30 d	60 d
	mm		$\mu mol \cdot m^{-2} \cdot s^{-1}$	
CK	7.47 ± 0.33^{b}	10.97 ± 0.41^{c}	7.99 ± 1.48^{b}	12.65 ± 0.59^{c}
CF-34	8.11 ± 0.17^{a}	11.73 ± 0.27^{b}	11.32 ± 1.51^{a}	16.73 ± 0.85^{b}
BR-17	8.09 ± 0.22^{a}	11.78 ± 0.12^{b}	12.51 ± 2.34^{a}	15.09 ± 0.65^{b}
BRC-17	8.17 ± 0.27^{a}	12.21 ± 0.19^{a}	12.22 ± 1.23^{a}	12.61 ± 1.30^{c}
BR-34	8.15 ± 0.13^{a}	12.03 ± 0.24^{ab}	11.95 ± 0.63^{a}	16.00 ± 2.61^{ab}
BRC-34	8.12 ± 0.25^{a}	12.27 ± 0.18^{a}	11.06 ± 2.14^{a}	15.27 ± 1.89^{b}
CB-34	8.08 ± 0.18^{a}	12.10 ± 0.21^{ab}	12.75 ± 2.32^{a}	17.41 ± 1.55^{ab}
CBC-34	8.20 ± 0.30^{a}	12.25 ± 0.09^{a}	12.20 ± 0.68^{a}	18.62 ± 0.52^{a}

Effect of biochar-based biogas residue fertilizer on cucumber root activity

Roots represent the sole organ for nutrient and water acquisition; thus, root activity is a critical determinant of crop yield and quality. As shown in Figure 2, compared with conventional chemical fertilizer (CF-34), the application of BRC and BR significantly enhanced cucumber root activity. The highest root activity was recorded in the BR-34 treatment, with BR-34 and BRC-34 exceeding CF-34 by 49.32% and 46.34%, respectively. When compared with BR alone at the lower N level (17 g N m^{-2}), the BC-amended treatments BRC-17 and CBC-34 increased root activity by 17.91% and 22.72% relative to their respective controls (BR-17 and CB-34). In contrast, nonsignificant difference was observed between BRC-34 and BR-34 at the higher N level.

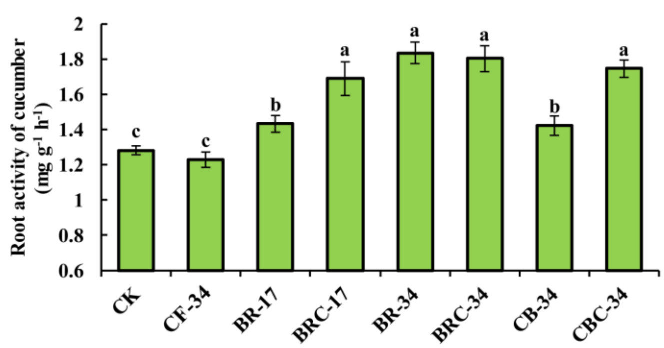

Figure 2. Root activity of cucumber at late fruiting stage under different fertilization treatments. Values are mean ± standard deviation. Different lowercase letters above values represent significant differences among treatments at $p < 0.05$. Eight fertilization treatments: No fertilizer blank control (CK); single conventional chemical fertilizer, 34 g N m^{-2} (CF-34); (sole cow dung biogas residue applied at 17 and 34 g N m^{-2} (BR-17, BR-34 respectively); sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2} (BRC-17, BRC-34 respectively); biogas residue mixed with chemical fertilizer, 34 g N m^{-2} (CB-34); biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2} (CBC-34). BRC-34 and CBC-34 share equal total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) application amounts, differing in cow dung biogas dosage: BRC-34 used 14 kg m^{-2} biogas residue without mineral fertilizer, whereas CBC-34 adopted 7 kg m^{-2} biogas residue plus matching N-P-K chemical fertilizers.

Root activity is strongly influenced by soil physical and chemical properties such as bulk density and water-holding capacity. Both BR (Pastorelli et al., 2021) and BC (Blanco-Canqui, 2017; Baiamonte et al., 2019) possess high specific surface area and a porous structure, which can improve soil aeration, reduce compaction, and enhance moisture retention. In this study, the addition of BC to BR likely created a more favorable rhizosphere environment, thereby stimulating root development and metabolic activity. This improvement in root vitality not only facilitates more efficient nutrient uptake, particularly under moderate N supply, but also strengthens plant resilience, establishing a stronger physiological foundation for subsequent yield formation and fruit quality enhancement. The pronounced effect of BRC treatments on root activity underscores the role of integrated organic amendments in building a healthy root system.

Comprehensive effects of biochar-based biogas residue fertilizer on yield and quality of cucumber

The application of BRC positively influenced both the productivity and quality of greenhouse cucumber in a synergistic manner. While the highest absolute yield was achieved with BR alone at high N (BR-34), BRC treatments, especially at the lower N level, effectively enhanced yield and markedly improved N use efficiency, indicating a more sustainable nutrient management strategy. More importantly, BRC application led to a discernible improvement in fruit quality: It elevated the content of nutritionally valuable components such as vitamin C and soluble protein, maintained or enhanced soluble sugar under combined fertilization, and significantly reduced the accumulation of nitrate—a key safety concern. The integration of these multi-dimensional quality parameters through a comprehensive evaluation further confirmed that BRC-amended treatments, particularly in combination with chemical fertilizer (CBC-34), achieved the highest overall quality score.

Effect of biochar-based biogas residue fertilizer on cucumber yield

The average cucumber yield across three replicate plots under different fertilizer treatments is presented in Figure 3. Compared with conventional chemical fertilizer (CF-34), the application of BR and BRC significantly increased yield. The highest yield was observed in the BR-34 treatment, with a mean value of 11 565.63 g. Yields in BR-34, BRC-34, and CBC-34 were 34.50%, 27.65%, and 14.88% higher than that in CF-34, respectively. The overall yield ranking was as follows: BR-34 ≥ BRC-34 > CBC-34 > CF-34 ≥ BRC-17 ≥ CB-34 > BR-17 > CK. Compared with RB alone, BC-amended treatments at the lower N level (17 g N m^{-2}), BRC-17 and CBC-34, exhibited a yield-promoting effect, whereas at the higher N level (34 g N m^{-2}), the addition of BC did not significantly enhance yield relative to BR-34.

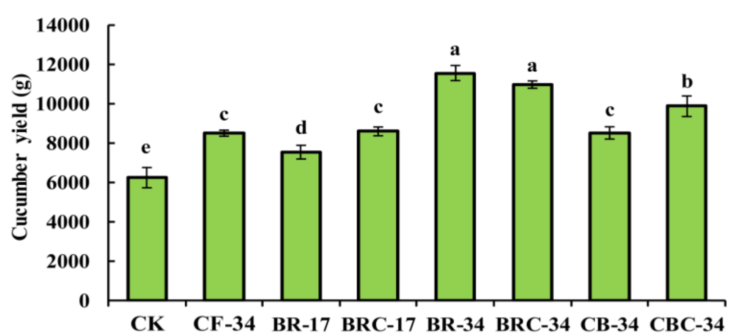

Figure 3. Total fresh yield of greenhouse cucumber under each fertilization treatment. Values are mean ± standard deviation. Different lowercase letters denote significant differences at $p < 0.05$. Eight fertilization treatments: No fertilizer blank control (CK); single conventional chemical fertilizer, 34 g N m^{-2} (CF-34); (sole cow dung biogas residue applied at 17 and 34 g N m^{-2} (BR-17, BR-34 respectively); sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2} (BRC-17, BRC-34 respectively); biogas residue mixed with chemical fertilizer, 34 g N m^{-2} (CB-34); biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2} (CBC-34). BRC-34 and CBC-34 share equal total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) application amounts, differing in cow dung biogas dosage: BRC-34 used 14 kg m^{-2} biogas residue without mineral fertilizer, whereas CBC-34 adopted 7 kg m^{-2} biogas residue plus matching N-P-K chemical fertilizers.

Nitrogen use efficiency (NUE) followed a distinct pattern. The highest NUE was recorded in BR-34, with the ranking being: BR-34 (156.44) > BRC-34 (139.10) > BRC-17 (138.16) > CBC-34 (106.81) > BR-17 (76.63) > CB-34 (66.85) > CF-34 (66.47). Specifically, NUE in BR-34 and BRC-34 was 135.35% and 109.27% higher than in CF-34, respectively, indicating substantial N loss from the chemical fertilizer treatment. The lower NUE in CB-34 and BR-17 suggests that a portion of applied N was either lost from the soil or immobilized in organic forms. Importantly, BRC-17 and CBC-34 showed significantly higher NUE than their respective counterparts (BR-17 and CB-34), demonstrating that the soil-amending effect of BRC not only supported yield but also enhanced N retention and utilization efficiency.

Effect of biochar-based biogas residue fertilizer on cucumber fruit quality

Cucumber fruit quality is highly sensitive to soil conditions, and fertilization strategies markedly influence its nutritional composition. Key quality indicators include soluble sugar, soluble protein, and vitamin C content, while nitrate accumulation is a critical safety parameter. The concentrations of these components across treatments are summarized in Table 6.

Table 6. Contents of soluble sugar, soluble protein, vitamin C and nitrate in cucumber fruits under different fertilization regimes. Values are mean ± standard deviation. Different lowercase letters within one column show significant differences at $p < 0.05$. CK: No fertilizer blank control; CF-34: single conventional chemical fertilizer, 34 g N m^{-2}; BR-17, BR-34: sole cow dung biogas applied at 17 and 34 g N m^{-2}; BRC-17, BRC-34: sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2}; CB-34: biogas residue mixed with chemical fertilizer, 34 g N m^{-2}; CBC-34: biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2}. BRC-34 and CBC-34 have identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) dosage; BRC-34 contains 14 kg m^{-2} cow dung biogas residue without mineral fertilizer, while CBC-34 only uses 7 kg m^{-2} biogas residue supplemented with N-P-K chemical fertilizers.

Treatment group	Soluble sugar	Soluble protein	Vitamin C	Nitrate
	%	mg g^{-1}	mg kg^{-1}	mg kg^{-1}
CK	2.05 ± 0.20^{d}	4.42 ± 0.12^{c}	61.32 ± 3.21^{c}	73.39 ± 2.77^{c}
CF-34	2.95 ± 0.24^{b}	5.26 ± 0.10^{a}	67.58 ± 0.79^{b}	99.47 ± 4.59^{a}
BR-17	2.34 ± 0.11^{c}	4.71 ± 0.07^{b}	62.33 ± 2.14^{c}	85.32 ± 0.83^{b}
BRC-17	2.40 ± 0.23^{c}	5.19 ± 0.20^{ab}	65.46 ± 4.27^{bc}	76.57 ± 5.64^{c}
BR-34	3.35 ± 0.12^{a}	4.86 ± 0.15^{b}	66.27 ± 0.93^{b}	93.64 ± 1.99^{a}
BRC-34	2.49 ± 0.13^{c}	5.32 ± 0.15^{a}	73.31 ± 1.64^{a}	83.14 ± 3.67^{b}
CB-34	2.44 ± 0.11^{c}	5.12 ± 0.24^{ab}	69.53 ± 2.72^{b}	88.49 ± 5.33^{ab}
CBC-34	2.75 ± 0.16^{b}	5.50 ± 0.15^{a}	78.16 ± 4.37^{a}	94.97 ± 1.73^{a}

The highest soluble sugar content was recorded in the BR-34 treatment, exceeding that in CF-34, BRC-34, and CK by 13.56%, 34.54%, and 63.41%, respectively. The overall ranking was: BR-34 > CF-34 ≥ CBC-34 > BRC-34 ≥ CB-34 ≥ BRC-17 ≥ BR-17 > CK. At the lower N level (17 g N m^{-2}), nonsignificant difference in sugar content was observed between BC-amended and biogas-residue-only treatments. However, at 34 g N m^{-2}, the addition of BC significantly reduced sugar content relative to BR-34. In contrast, the combined application of BRC with chemical fertilizer (CBC-34) increased soluble sugar by 12.70% compared with CB-34. Soluble sugar synthesis depends strongly on root acquisition of soil nutrients. As shown above, BC-based amendments enhanced root activity, and when supplemented with chemical fertilizer (CBC-34), they compensated for the short-term nutrient adsorption by BC, thereby improving carbohydrate accumulation in fruits.

The highest soluble protein content occurred in CBC-34, which was 7.42%, 4.56%, and 24.43% higher than in CB-34, CF-34, and CK, respectively. Compared with BR alone, BC-based treatments generally increased protein content, with the most pronounced effect in BRC-34 (9.47% higher than BR-34). Nitrogen is the primary substrate for protein synthesis, and protein content is expected to correlate positively with soil available N. However, in this experiment, protein levels did not strictly follow soil N availability; for instance, CF-34 (highest early-stage soil available N) and BRC-34 (lower available N) showed comparable protein contents. This discrepancy may be explained by: (1) A saturating N supply across treatments that met the cucumber's protein-synthesis demand; (2) improved root efficiency induced by BC-based amendments, enabling adequate N uptake even under lower soil N availability (Backer et al., 2017; Song et al., 2020); and (3) interactive effects between N and K, where protein content may increase with K supply under limited N, but decrease with added N when K is deficient.

Vitamin C, an essential nutrient that humans cannot synthesize, is a key quality attribute of fresh vegetables. The highest vitamin C concentration was found in CBC-34, exceeding CB-34 and CF-34 by 12.41% and 15.66%, respectively. While previous studies reported that organic fertilizers or their combination with chemical fertilizers can enhance vitamin C in cucumbers (Al-Rubaie et al., 2025), nonsignificant differences were observed among BR-34, CB-34, and CF-34 in this trial. Notably, BRC treatments significantly increased vitamin C relative to BR alone at the same N level, likely due to BC-mediated adjustments in soil N-P-K ratios and improved rhizosphere conditions (Kumar et al., 2023).

Nitrate accumulation in vegetables is a safety concern because nitrate can be reduced to nitrite in the human body and form carcinogenic N-nitroso compounds (Seyyedsalehi et al., 2023). The former Chinese national safety standard for nitrate in fruiting vegetables sets a limit of 600 mg kg^{-1}. All treatments in this study produced nitrate levels well below this threshold. The highest nitrate content occurred in CF-34, while CK and BR-17 showed the lowest values. Within the same fertilizer type, the lower N rate (17 g m^{-2}) led to lower nitrate accumulation than the higher rate (34 g m^{-2}). At the same N level, BR-34, CF-34, and CB-34 did not differ significantly. Importantly, BRC treatments significantly reduced nitrate content compared with BR alone. Crop nitrate uptake reflects soil nitrate availability; excessive soil nitrate leads to accumulation in fruits when assimilation capacity is exceeded. Biochar surfaces contain oxygen-functional groups that can adsorb ammonium-N (NH_4^+-N) (Fan et al., 2019), thereby promoting nitrification (Dorner and Behrens, 2024). This mechanism likely contributed to the lower nitrate concentrations in fruits from BC-amended treatments.

Comprehensive quality evaluation of cucumber

To integrally assess the effects of different fertilization regimes on cucumber fruit quality, a fuzzy mathematics membership function was employed, which allows for a relative ranking of overall quality across treatments. As summarized in Table 7, among all treatments, the combined application of chemical fertilizer and BRC (CBC-34) yielded the highest comprehensive quality score of 0.73, followed by the BRC treatment BRC-34 with a score of 0.68. The overall quality ranking was: CBC-34 > BRC-34 > BRC-17 > CB-34 > CF-34 > BR-34 > BR-17 > CK. Notably, at the same N application level, treatments amended with BRC consistently achieved higher comprehensive quality scores compared with those receiving chemical fertilizer alone or BR alone.

Table 7. Single index membership value and comprehensive quality score of cucumber calculated by fuzzy mathematics membership function. CK: No fertilizer blank control; CF-34: single conventional chemical fertilizer, 34 g N m^{-2}; BR-17, BR-34: sole cow dung biogas applied at 17 and 34 g N m^{-2}; BRC-17, BRC-34: sole biochar-based biogas residue without chemical fertilizer at 17 and 34 g N m^{-2}; CB-34: biogas residue mixed with chemical fertilizer, 34 g N m^{-2}; CBC-34: biochar-based biogas residue combined with chemical fertilizer, 34 g N m^{-2}. BRC-34 and CBC-34 have identical total N (34 g N m^{-2}) and biochar (3 kg m^{-2}) dosage; BRC-34 contains 14 kg m^{-2} cow dung biogas residue without mineral fertilizer, while CBC-34 only uses 7 kg m^{-2} biogas residue supplemented with N-P-K chemical fertilizers.

Treatment group	Soluble sugar	Soluble protein	Vitamin C	Nitrate	Average score
CK	0.00	0.00	0.00	1.00	0.27
CF-34	0.69	0.78	0.37	0.00	0.37
BR-17	0.22	0.27	0.06	0.54	0.24
BRC-17	0.27	0.71	0.25	0.88	0.50
BR-34	1.00	0.41	0.29	0.22	0.36
BRC-34	0.34	0.83	0.71	0.63	0.68
CB-34	0.30	0.65	0.49	0.42	0.48
CBC-34	0.54	1.00	1.00	0.17	0.73

CONCLUSIONS

The present study investigated the effects of biochar-based biogas residue composite fertilizer (BRC) on plant growth, physiological traits, root activity, yield, N use efficiency (NUE), and fruit quality of greenhouse cucumber under different nitrogen application levels and combined fertilization modes. Two treatments with equal total N input (34 g N m^{-2}), namely BRC-34 and CBC-34, differed markedly in biogas residue dosage: BRC-34 received 14 kg·m^{-2} cow dung biogas residue without additional chemical fertilizer, while CBC-34 contained only 7 kg·m^{-2} biogas residue combined with mineral N-P-K fertilizers. Compared with conventional chemical fertilizer treatment, sole application of BRC significantly promoted cucumber vegetative growth and improved root activity. Although the maximum fruit yield was obtained under high-rate single biogas residue treatment (BR-34), BRC-34 achieved the highest NUE, increasing by 109.27% relative to the conventional chemical fertilizer treatment (CF-34), which effectively mitigated N surplus risk in greenhouse soil. In terms of fruit quality, BRC application elevated soluble protein and vitamin C concentrations and reduced nitrate accumulation in cucumber fruits. The fuzzy comprehensive evaluation integrating multiple quality indicators demonstrated that CBC-34 exhibited the optimal comprehensive fruit quality score of 0.73. The positive effects of the composite fertilizer mainly stemmed from the synergistic interaction between biochar and biogas residue; biochar can adsorb nutrients and realize slow nutrient release, matching the continuous mineralization of organic matter from biogas residue and synchronizing soil nutrient supply with cucumber N demand. Overall, the combined application mode CBC-34 is recommended as a sustainable fertilization strategy for greenhouse cucumber production, which balances yield, N utilization efficiency and edible safety under circular planting systems. Overall, this research highlights BRC as a promising integrated amendment for advancing sustainable greenhouse cucumber cultivation, offering a practical strategy to reconcile productivity, resource efficiency, and high-quality vegetable production within a circular agricultural framework.

Author contribution

Conceptualization: X.Y. Methodology: X.M., Y.X. Formal analysis: F.C., Y.X. Investigation: X.M. Writing-original draft: X.M. Writing-review & editing: F.C., Y.Z. Supervision: Y.Z., X.Y. Funding acquisition: L.Q., X.Y. All co-authors reviewed the final version and approved the manuscript before submission.

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