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Biochar-Based Urea Enhances Yield and Quality of Lady's Finger (*Abelmoschus esculentus* L.): A Pathway Towards Sustainable Nitrogen Management

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ABSTRACT

Low nitrogen-use efficiency (NUE) and excessive application of nitrogen fertilizers pose serious threats to sustainable agriculture, causing severe soil fertility depletion, environmental degradation, and economic losses. Biochar-based nitrogen fertilizers (BBNFs) offer a promising strategy to enhance NUE through controlled nutrient release and improved soil quality. However, the effect of BBNFs on lady's finger (*Abelmoschus esculentus* L.) production is still limited. Therefore, this study was conducted to evaluate the effects of BBNFs on the growth, yield, and nutritional quality of lady's finger. Seven treatments were employed, including conventional urea, biochar-mixed urea (BMU), and biochar-coated urea (BCU). Results demonstrated that BCU (T7) significantly ($p \leq 0.05$) outperformed all other treatments, producing the highest number of leaves, leaf area, plant height, photosynthetic rate, biomass accumulation, and pod yield (13.62 t ha^{-1}), representing a 65.9% increase over conventional urea. BCU also achieved the greatest agronomic nitrogen-use efficiency (24.27 g g^{-1}), harvest index (55.41%), and cost-income ratio (2.63). Nutritional quality traits, including TSS, ascorbic acid, total flavonoids, protein, etc., were also significantly enhanced under BCU. The findings highlight the potential of BCU as a sustainable fertilizer management strategy that improves yield, fruit quality, and economic returns in lady's finger, while providing actionable approaches to enhance NUE and mitigate environmental degradation.

1 | Introduction

Lady's finger (*Abelmoschus esculentus* L.), a member of the Malvaceae family, is an important annual vegetable crop widely cultivated in tropical and subtropical regions. The global cultivated area of the crop was estimated at 2.95 million hectares, with a total production of 11.52 million tons (FAOSTAT 2024). Bangladesh, India, and the USA together account for over 63% of global production (FAOSTAT 2024). The crop's adaptability, heat tolerance, and low input requirements enable its successful cultivation across diverse soils under both rainfed and irrigated conditions. The tender green pods are rich in carbohydrates, proteins, vitamins, minerals, folic acid, and dietary fiber (Patra et al. 2023; Gaur et al. 2025). In addition to its nutritional importance, lady's finger exhibits several medicinal properties, including diuretic, ophthalmic, anticancer, and cardioprotective

Abbreviations: ANUE, agronomic nitrogen use efficiency; BBFs, biochar-based fertilizers; BBNFs, biochar-based nitrogen fertilizers; BBSRFs, biochar-based slow-release fertilizers; BBUFs, biochar-based urea fertilizers; BCU, biochar-coated urea; BMU, biochar-mixed urea; CIR, cost-income ratio; DAS, days after sowing; Fw, fresh weight; HI, harvest index; NUE, nitrogen-use efficiency; PCA, principal component analysis; SRFs, slow-release fertilizers; TA, titratable acidity; TSS, total soluble solids.

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effects (Romdhane et al. 2020; Gaur et al. 2025). Its high soluble fiber content and low glycemic index make it particularly suitable for diabetic diets (Ahmad et al. 2025).

Efficient nutrient management is essential for optimizing the growth and yield of lady's finger, whereas poor nutrient practices can significantly reduce productivity. With the global population projected to reach 9.7 billion by 2050, food demand is expected to increase sharply (Joshi et al. 2024). The simultaneous rise in food demand and reduction in arable land continue to exert pressure on global agricultural production. Chemical fertilizers have therefore played a pivotal role in enhancing food production, contributing to nearly 50% of yield increases worldwide (Chen et al. 2018). Nitrogen (N) is one of the most essential macronutrients for plant growth and the most widely used fertilizer element. Global nitrogen fertilizer consumption reached 115.03 million metric tons in 2024 (IFASTAT 2024). In Bangladesh, nitrogen fertilizer consumption has increased by 30.7% over the last decade, with urea accounting for approximately 75% of total nitrogen applied (IFASTAT 2024; Kamuruzzaman et al. 2024). In lady's finger, nitrogen plays a critical role in promoting vegetative growth, chlorophyll synthesis, and fruit development (Lokesh et al. 2024; Xu et al. 2024). Studies have shown that higher nitrogen fertilization can increase fruit number by up to 15.8% (Santos et al. 2019).

Excessive use of nitrogen fertilizers has become common among farmers seeking to maximize vegetable yields. Application rates often exceed crop requirements severalfold, resulting in substantial nutrient losses and environmental degradation (Bhatt et al. 2025; Martínez-Dalmau et al. 2021). On average, only 20%–40% of applied nitrogen is absorbed by crops, while 60%–80% is lost through volatilization, leaching, and denitrification (Govindasamy et al. 2023; Qasim et al. 2022). Globally, approximately 200 million tons of reactive nitrogen are released into the environment each year (Nations Environment Programme 2019), contributing to groundwater contamination, eutrophication, greenhouse gas emissions, and soil degradation (Adebanjo-Aina and Oludoye 2025; Bijay-Singh and Craswell 2021; Wang et al. 2019). Long-term overuse of synthetic N fertilizers also disrupts soil nutrient balance, depletes organic matter, and induces micronutrient deficiencies (Bisht and Chauhan 2020; Li et al. 2021). Moreover, excessive nitrate accumulation in vegetables poses significant food safety risks, including digestive system carcinogenesis (Dodocioiu et al. 2025). Ensuring food safety and sustainable vegetable production has therefore become a major global concern. Recent research has focused on developing environmentally friendly fertilizers, improving NUE, and reducing nitrate accumulation in crops (Bhatt et al. 2025; Ahmed et al. 2020). Traditional approaches to enhancing nitrogen fertilizer efficiency—such as polymer or sulfur-coated urea, urease inhibitors, and urea—formaldehyde—are effective but often costly and require advanced technical expertise (Lawrencia et al. 2021). Enhancing fertilizer efficiency remains essential for maximizing crop productivity while maintaining economic and environmental sustainability.

Slow-release fertilizers (SRFs) offer an effective solution by gradually releasing nutrients in synchrony with crop requirements, thereby enhancing nutrient uptake and reducing environmental losses (Govil et al. 2024). Among SRFs, biochar-based fertilizers (BBFs) have attracted increasing attention due to their dual role in nutrient release regulation and soil improvement (Wang et al. 2022). Biochar, a carbon-rich material produced via pyrolysis of organic biomass under limited oxygen conditions, possesses a high surface area, porous structure, graphitic domains, and abundant functional groups (e.g., hydroxyl, carboxyl, carbonyl), which enhance nutrient retention through physical and chemical mechanisms (Mulabagal et al. 2025; Varkolu et al. 2025). Extensive studies have demonstrated that biochar improves soil fertility, enhances crop yields, mitigates greenhouse gas emissions, immobilizes contaminants, and promotes microbial activity (Mulabagal et al. 2025; Amirahmadi et al. 2025; Dong et al. 2021). BBNFs have been shown to reduce nitrogen losses, improve NUE, and stimulate plant growth compared with conventional urea (Dong et al. 2021; Puga et al. 2020). BBNFs can be produced by blending biochar with inorganic fertilizers or by coating fertilizer granules with biochar (Bi et al. 2024; dos Santos et al. 2025). Recent studies have reported that BBNFs significantly reduce nitrogen leaching and ammonia volatilization while increasing NUE by 12%–20% and improving crop yields across rice, wheat, maize, soybean, and barley (Wang et al. 2022; Dong et al. 2022; Shi et al. 2020).

Despite the numerous importance of lady's finger as a nutritionally and economically valuable crop, limited research has evaluated the impact of biochar-based slow-release urea fertilizers on its growth and productivity. Therefore, the main objective of this study was to evaluate the effects of biochar-coated and biochar-mixed urea fertilizers on the growth, yield, and nutritional quality of lady's finger to promote sustainable fertilizer management and minimize environmental losses.

2 | Materials and Methods

2.1 | Experimental Site and Materials

The field experiment was carried out at the Horticulture Research Field, Exim Bank Agricultural University Bangladesh, Chapai-Nawabganj (24.60° N latitude, 88.27° E longitude). The site is situated at an elevation of approximately 25 m above sea level and is characterized by a tropical wet and dry (savanna) climate, with average temperatures ranging from 25°C to 35°C and an annual mean rainfall of about 1476 mm (Weather Spark 2025; Bangladesh Water Development Board 2024). Laboratory analyses were conducted at the Soil Science and Postharvest Technology Laboratories, Patuakhali Science and Technology University, Patuakhali, Bangladesh. Lady's finger seeds of the variety Ropon Hybrid Okra-01 were sourced from Square Pharmaceuticals PLC, Bangladesh, and used as planting material. A preliminary soil analysis conducted before the experiment classified the soil as clay loam. The detailed soil properties of the experimental site are presented in Table 1.

2.2 | Experimental Design and Treatments

A single factor Randomized Complete Block Design (RCBD) was employed to evaluate the effect of BBUFs on crop performance. The experiment consisted of seven treatments with three replications for each treatment. Among these, one treatment served

as the negative control (no urea) and another as the positive control (100 g urea without biochar). The treatment details are as follows:

- T1: No urea (negative control)
- T2: 100 g urea (positive control)
- T3: Urea, biochar, humic acid, and soil mixed at a 10:1:1:1 ratio
- T4: Urea, biochar, humic acid, and soil mixed at a 10:2:1:1 ratio
- T5: Urea, biochar, humic acid, and soil mixed at a 10:3:1:1 ratio
- T6: Urea, biochar, humic acid, and soil mixed at a 10:4:1:1 ratio
- T7: Biochar-coated urea.

TABLE 1 | Physicochemical properties of the soil at the experimental site.

Parameter	Unit	Value
pH	—	6.10
Organic matter	%	1.36
Total nitrogen	%	0.08
Available phosphorus	mg kg^{-1} soil	19.73
Available sulphur	mg kg^{-1} soil	14.80
Available zinc	mg kg^{-1} soil	1.05
Available boron	mg kg^{-1} soil	0.60
Exchangeable potassium	meq 100 g^{-1} soil	0.19
Exchangeable calcium	meq 100 g^{-1} soil	5.32
Exchangeable magnesium	meq 100 g^{-1} soil	2.39
Exchangeable magnesium	meq 100 g^{-1} soil	0.21

Treatment applications were split into four doses following the ratio of 50:20:15:15 (w/w), applied during final land preparation, and at 20, 40, and 60 days after sowing (DAS) of seeds. Except for urea, all other fertilizers were applied following the Agro Technology Hand Book (Bangladesh Agricultural Research Institute 2024) recommended fertilizer management practices for lady's finger. A schematic representation of the experimental layout is shown in Figure 1.

2.3 | Preparation of Biochar-Coated Urea

BCU was prepared using agricultural-grade super granule urea (46% N) as the core material, rice husk biochar as the coating agent, and humic acid and molasses as binders (Figure 2). Rice husk biochar was produced via slow pyrolysis at 600°C, then cooled, ground, and sieved through a 100-mesh screen. The biochar exhibited a pH of 7.9, ash content of 28.5%, C = 476 mg kg^{-1}, H = 33.6 mg kg^{-1}, N = 4.1 mg kg^{-1}, p = 1.51 mg kg^{-1}, K = 17.02 mg kg^{-1}, O/C molar ratio = 0.32, H/C molar ratio = 0.61, and EC = 0.53 dS m^{-1}. Its porous characteristics included a BET specific surface area (SBET) of 9.81 m^2 g^{-1}, a total pore volume (Vt) of 0.0128 cm^3 g^{-1}, and an average pore width (Dave) of 5.25 nm. Based on preliminary studies, BCU was formulated in a biochar: urea: humic acid ratio of 3:10:1 (w/w). Molasses diluted with water (1:2, v/v) served as the liquid

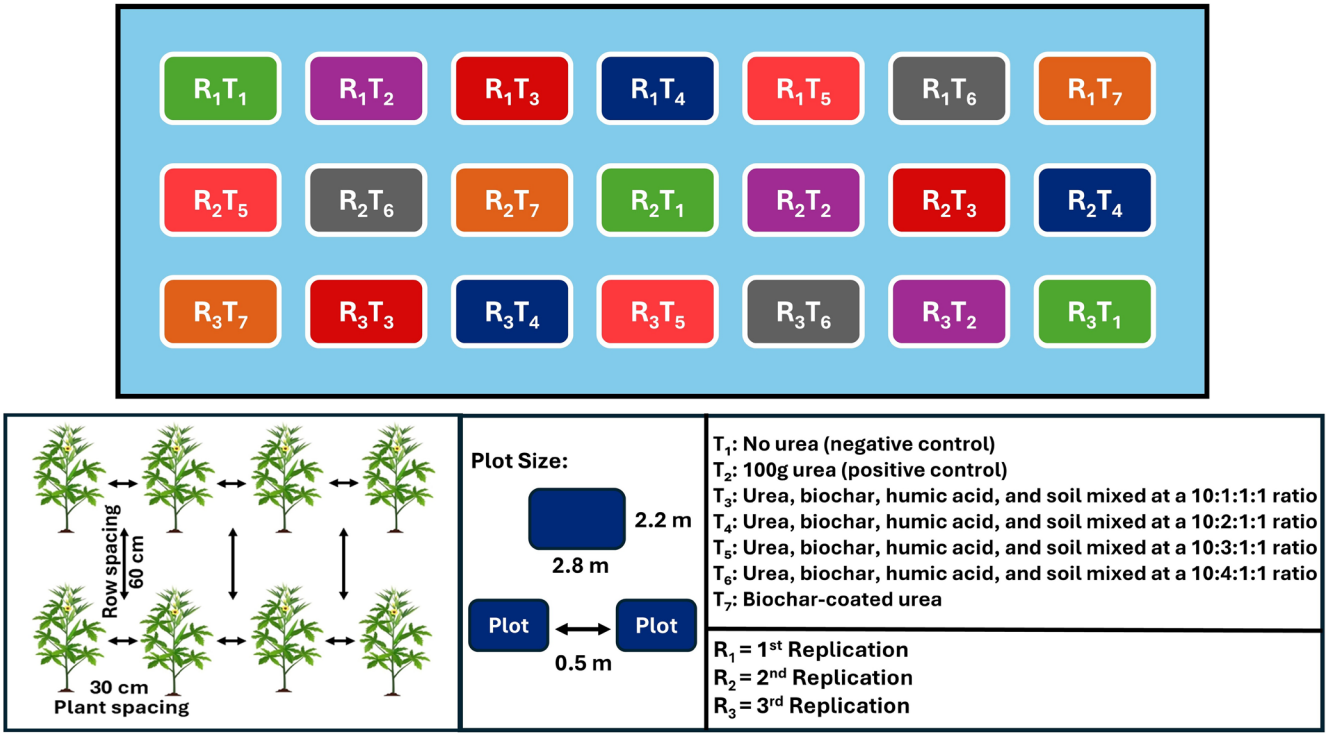


FIGURE 1 | Layout of the field experiment.

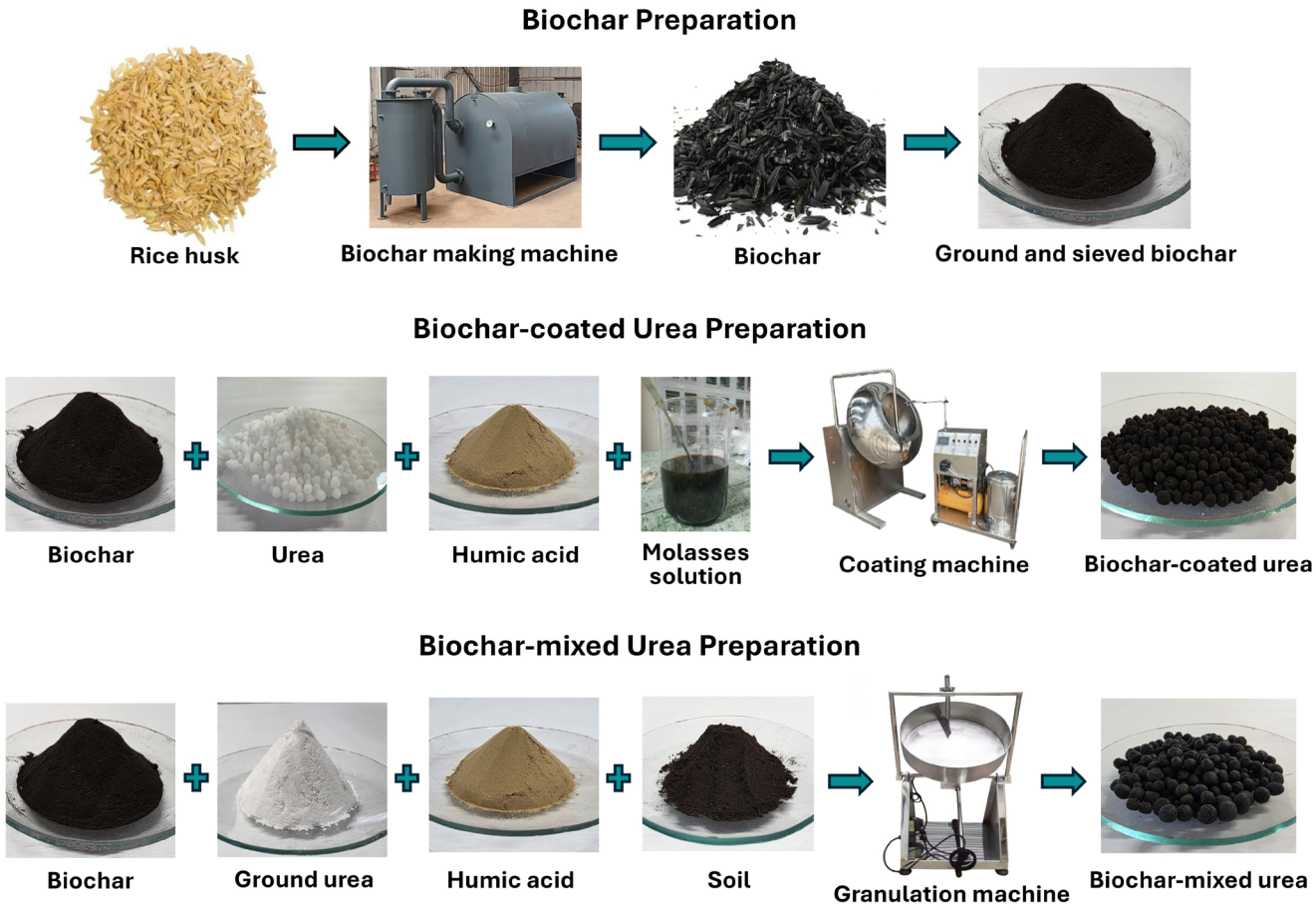


FIGURE 2 | Schematic representation of the preparation of biochar-based urea fertilizers.

binder. Urea granules (3 ~ 4 mm) were first mixed with humic acid for 5 min, then coated in a coating machine (ZL30, Golden International Building, Kangtai Rd., Xingyang, China) operated at 60 rpm with the heating function on. Once the urea surface temperature reached 60°C, the molasses solution was sprayed onto the granules while biochar was simultaneously added. The coating process continued for 10 min. The coated granules were then dried at 30°C for 4 h. The final BCU (T7) product had a total nitrogen content of 31.87%.

2.4 | Preparation of Biochar-Mixed Urea

Biochar-mixed urea (BMU) was prepared using rice husk-derived biochar (Section 2.3), agricultural-grade urea (46% N), humic acid, and soil (Figure 2). Biochar and urea were finely ground and sieved through a 100-mesh strainer to ensure uniform particle size. The components were then thoroughly mixed in different weight ratios (w/w) of urea:biochar:humic acid: soil, specifically 10:1:1:1 (T3), 10:2:1:1 (T4), 10:3:1:1 (T5), and 10:4:1:1 (T6) in a plastic pot to achieve a homogeneous blend. The blended mixtures were granulated using a disc granulator to produce granules. During granulation, wood vinegar diluted 1:200 with water (approximately 10% of the granule mass) was evenly sprayed to enhance binding properties. The resulting moist granules were dried in an oven at 60°C for 3 h to achieve optimal hardness and stability. The final BMU granules were black, spherical particles with an average diameter of 4 ~ 5 mm and hardness ranging from 13.84 to 14.36 N. The total nitrogen contents of the treatments were as follows: T3 = 40.23%, T4 = 36.45%, T5 = 33.12%, and T6 = 26.86%.

2.5 | Assessment of Treatment Effects on Lady's Finger

2.5.1 | Growth, Physiological, and Yield Measurements

The growth and physiological responses of lady's finger to different treatments were assessed during the experimental period. Data were recorded for the number of leaves, leaf area (cm^2), plant height (cm), and stem diameter (cm) at 20, 40, 60, and 80 DAS. Leaf area was measured using a leaf area meter (Systronics 211, India). Photosynthetic rate was recorded at 40 DAS using a portable photosynthesis system (LI-6200, LI-COR Inc., Lincoln, NE, USA) under ambient conditions. Phenological traits, including days to first flowering and days to first pod harvest, were also recorded. At harvest (80 DAS), the following agronomic and yield parameters were measured: individual pod weight (g), pod length (cm), pod diameter (cm), number of branches per plant, root length (cm), fresh biomass per plant (g), dry biomass per plant (g), and total pod yield per hectare ($t\,ha^{-1}$). Total nitrogen (N), phosphorus (P), and potassium (K) contents per plant were determined following the methods described by Labib et al. (2026). Pod moisture content (%), dry matter content (%), harvest index (HI), agronomic efficiency of applied nitrogen

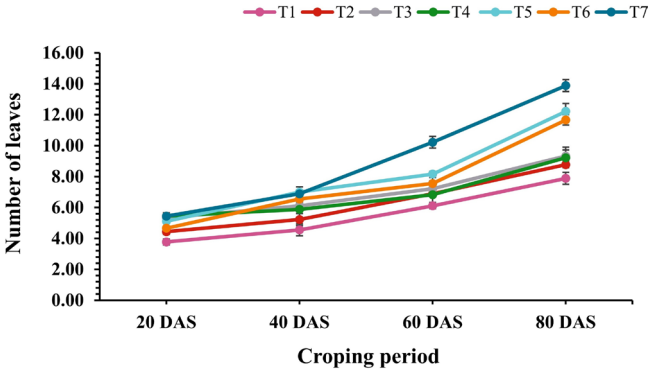


FIGURE 3 | Effects of biochar-based urea fertilizers on number of leaves of lady's finger.

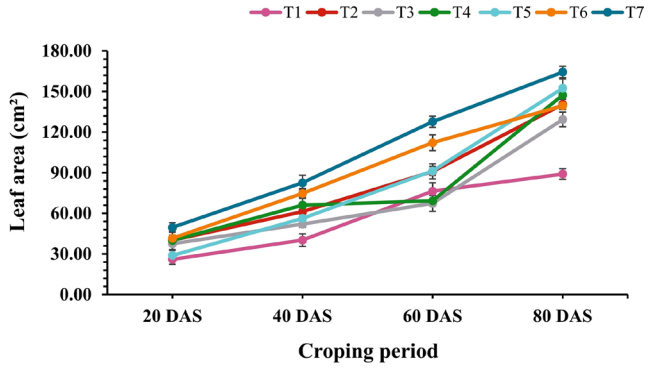


FIGURE 4 | Effects of biochar-based urea fertilizers on leaf area of lady's finger.

(ANUE), and cost-income ratio (CIR) were calculated using the following formulas:

$$\text{Pod moisture content (\%)} = \frac{\text{Pod Fresh Weight (g)} - \text{Pod Dry Weight (g)}}{\text{Pod Fresh Weight (g)}} \times 100$$

$$\text{Dry matter content (\%)} = \frac{\text{Dry Biomass plant}^{-1}\text{ (g)}}{\text{Fresh Biomass plant}^{-1}\text{ (g)}} \times 100$$

$$\text{HI (\%)} = \frac{\text{Fruit yield}}{\text{Biological yield}} \times 100$$

$$\text{ANUE (g/g)} = \frac{\text{Yield in treated plot} - \text{Yield in control plot}}{\text{Amount of N applied}}$$

$$\text{CIR (Tk.)} = \frac{\text{Income generated}}{\text{Total cost occurred}}$$

2.5.2 | Fruit Nutritional Quality Analysis

The pH of lady's finger pods was measured using a calibrated glass electrode pH meter (GLP 21, Crison, Barcelona, EEC) with pH 4.0 and 7.0 buffer solutions. Total soluble solids (TSS) were determined using a digital refractometer (BOECO, Germany) and expressed as °Brix, with temperature correction applied at 20°C (Uddin et al. 2026). Titratable acidity (TA) was measured following Labib et al. (2025). Briefly, 10 g of pulp was homogenized with 90 mL of distilled water, filtered through muslin cloth, and titrated with 0.1 N NaOH using phenolphthalein as an endpoint indicator. The results were expressed as a percentage. Ascorbic acid content was determined according to the methods described by Ahmed et al. (2024). In this procedure, 10 mL of juice was diluted to 100 mL with 0.4% oxalic acid, and a 5 mL aliquot was titrated with 2,6-dichloroindophenol. The ascorbic acid content was calculated and expressed as mg 100 g^{-1} fresh weight (Fw). Total phenolics were estimated following Labib et al. (2025) by measuring absorbance at 760 nm and calculating content against a gallic acid standard curve (mg GAE 100 g^{-1} Fw). Total flavonoid content was analyzed as per Wakchaure et al. (2023) and expressed as mg catechin equivalents (CAE) g^{-1}. Crude protein was analyzed according to Romdhane et al. (2020) and expressed as mg g^{-1} Fw.

2.6 | Statistical Analysis

All data were expressed as mean ± standard deviation (SD) based on three independent replicates. Statistical analyses were performed using R software (version 4.5.3). One-way analysis of variance (ANOVA) was used to evaluate treatment effects on all measured variables, and mean comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at a 5% significance level ($p \leq 0.05$). Pearson correlation and principal component analysis (PCA) were conducted to evaluate relationships and identify data patterns.

3 | Results

3.1 | Growth, Physiological, and Yield Traits

Significant differences ($p \leq 0.05$) were observed among treatments for growth, physiological, and yield traits of lady's finger. The number of leaves varied significantly ($p \leq 0.05$) among treatments across all growth periods (Figure 3). Treatment T7 consistently produced the highest number of leaves at each observation, recording 5.44, 6.89, 10.22, and 13.88 leaves $plant^{-1}$ at 20, 40, 60, and 80 DAS. In contrast, the negative control T1 exhibited the lowest values (3.77, 4.55, 6.11, and 7.88 leaves $plant^{-1}$), while the positive control T2 produced intermediate leaf numbers (4.44, 5.22, 6.89, and 8.77 leaves $plant^{-1}$). Relative to the positive control, T7 increased leaf number by 22.5%, 32.0%, 48.3%, and 58.3% at 20, 40, 60, and 80 DAS. Leaf area was also significantly ($p \leq 0.05$) influenced by treatment application (Figure 4). The maximum leaf area was recorded in T7, with values of 49.62, 82.63, 127.76, and 164.44 cm^2 at 20, 40, 60, and 80 DAS. The positive control T2 produced moderate leaf area (40.21, 61.34, 90.97, and 140.51 cm^2), whereas the negative control T1 consistently resulted in the lowest leaf area (26.08, 40.24, 76.39, and 89.08 cm^2). Compared with T2, treatment T7 enhanced leaf area by 23.4%, 34.7%, 40.5%, and 17.0% at the corresponding growth stages.

Plant height differed significantly ($p \leq 0.05$) among treatments throughout the growing period (Figure 5). The tallest plants were observed under T7, measuring 23.69, 31.74, 41.15, and 56.03 cm at 20, 40, 60, and 80 DAS. Plants grown under the positive control T2 attained heights of 18.94, 26.06, 30.71, and 43.30 cm at the same stages. Accordingly, treatment T7 increased plant height by 25.1%,

21.8%, 34.0%, and 29.4% over the positive control at successive observation times. Stem diameter was significantly ($p \leq 0.05$) affected by treatment application (Figure 6). The highest stem diameter was recorded in T6 (1.76, 2.54, 3.73, and 4.03 cm at 20, 40, 60, and 80 DAS), which was statistically comparable to T7 (1.61, 2.57, 3.40, and 3.96 cm). The positive control T2 exhibited moderate stem thickness (1.40, 2.20, 3.00, and 3.25 cm). At 80 DAS, treatments T6 and T7 increased stem diameter by 24.0% and 21.8% compared with the positive control.

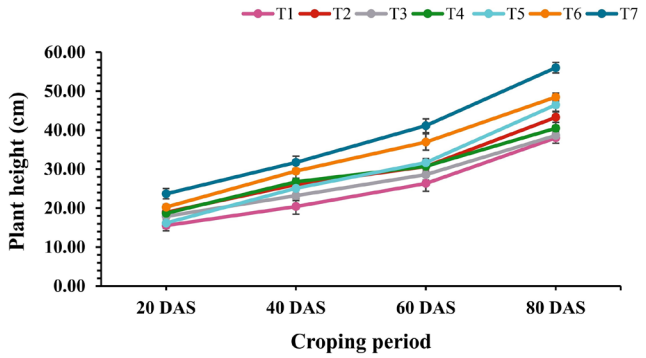


FIGURE 5 | Effects of biochar-based urea fertilizers on plant height of lady's finger.

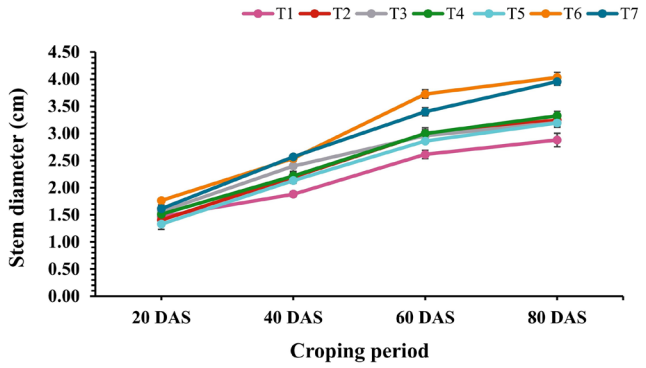


FIGURE 6 | Effects of biochar-based urea fertilizers on stem diameter of lady's finger.

Photosynthetic rate differed significantly ($p \leq 0.05$) among treatments (Table 2). At 40 DAS, treatment T7 achieved the highest rate at $13.21 \pm 0.08\ \mu mol\ m^{-2} s^{-1}$, representing a 31.3% increase over the positive control T2, which recorded $10.06 \pm 0.16\ \mu mol\ m^{-2} s^{-1}$. The lowest photosynthetic rate was observed in the negative control T1 at $6.19 \pm 0.09\ \mu mol\ m^{-2} s^{-1}$. Phenological traits varied significantly ($p \leq 0.05$) among treatments (Table 2). Time to first flowering was longest in T1 at 54.33 ± 0.34 days and shortest in T4 and T6 at 50.56 ± 0.20 days, which were statistically comparable to T7 at 50.67 ± 0.34 days. Compared with T2 at 51.22 ± 0.19 days, T4 and T6 reduced flowering time by 1.29%, and T7 by 1.07%. Days to first pod harvest followed a similar trend, with T1 requiring the longest duration at 60.33 ± 0.58 days, while T7 recorded the earliest harvest at 56.55 ± 0.19 days, comparable to T6. Compared to T2 at 58.89 ± 0.51 days, T7 reduced the time to pod harvest by 3.98%.

Significant ($p \leq 0.05$) variations were observed in individual pod weight, pod length, pod diameter, and pod moisture content (Tables 2 and 3). Treatment T7 produced the highest individual pod weight of 14.34 ± 0.32 g, along with the greatest pod length at 12.97 ± 0.51 cm and pod diameter at 4.89 ± 0.09 cm, whereas T1 consistently recorded the lowest values. The positive control T2 showed intermediate performance, with a pod weight of 10.70 ± 0.47 g, pod length of 9.98 ± 0.18 cm, and pod diameter of 4.55 ± 0.10 cm. Pod moisture content also varied significantly ($p \leq 0.05$) among treatments, with the highest value recorded in T5 at 83.85% and the lowest in T3 at 80.57%, which was statistically comparable to T2. Branch number per plant differed significantly ($p \leq 0.05$) at 80 DAS (Table 3). Again, treatment T7 produced the highest number of branches at 5.89 ± 0.20 plant^{-1}, representing a 65.9% increase over T2 at 3.55 ± 0.19 plant^{-1}, while T1 recorded the lowest branching at 2.66 ± 0.34 plant^{-1}. At harvest, the longest root length was

TABLE 2 | Effects of biochar-based urea fertilizers on photosynthetic rate, flowering time, pod harvest time, and yield attributes of lady's finger.

Treatment	Photosynthesis rate ($\mu mol\ m^{-2} s^{-1}$)	Days to first flowering	Days to first pod harvest	Individual pod weight (g)	Pod length (cm)
T1	6.19 ± 0.09^{g}	54.33 ± 0.34^{a}	60.33 ± 0.58^{a}	9.18 ± 0.65^{d}	9.90 ± 0.60^{c}
T2	10.06 ± 0.16^{d}	51.22 ± 0.19^{c}	58.89 ± 0.51^{b}	10.70 ± 0.47^{c}	9.98 ± 0.18^{c}
T3	8.31 ± 0.21^{f}	51.44 ± 0.38^{c}	59.78 ± 0.19^{a}	9.95 ± 0.56^{cd}	10.05 ± 0.29^{c}
T4	11.26 ± 0.10^{c}	50.56 ± 0.20^{d}	58.11 ± 0.19^{c}	10.43 ± 0.13^{c}	10.55 ± 0.27^{c}
T5	11.82 ± 0.06^{b}	52.22 ± 0.19^{b}	58.33 ± 0.34^{bc}	10.78 ± 0.64^{c}	10.21 ± 0.31^{c}
T6	9.68 ± 0.20^{e}	50.56 ± 0.20^{d}	57.00 ± 0.34^{d}	12.59 ± 0.39^{b}	12.04 ± 0.74^{b}
T7	13.21 ± 0.08^{a}	50.67 ± 0.34^{d}	56.55 ± 0.19^{d}	14.34 ± 0.32^{a}	12.97 ± 0.51^{a}
Level of sig.	***	***	***	***	***
CV (%)	1.18	0.51	0.64	4.25	4.35
LSD	0.210	0.467	0.661	0.836	0.830

Note: Here, all values are expressed as mean ± SD. Means followed by different superscript letters differ significantly at $p \leq 0.05$ according to Tukey's HSD test.
Significance levels: ***$p \leq 0.001$.
Abbreviations: CV, coefficient of variation; NS, not significant.

observed in T5 at 23.70 cm, which was statistically comparable to T3 and T7. In contrast, the shortest root length was observed in T2 at 20.14 cm.

Fresh and dry biomass plant^{-1}, dry matter content, NPK contents, and total yield differed significantly ($p \leq 0.05$) among treatments (Tables 4 and 5). Treatment T7 consistently outperformed all other treatments, producing a fresh biomass of 91.64 g plant^{-1}, a dry biomass of 21.42 g plant^{-1}, a dry matter content of 23.37%, and a total yield of 13.62 t ha^{-1}. In contrast, T1 recorded the lowest values for these traits. The positive control T2 yielded 61.44 g fresh biomass plant^{-1}, 13.82 g dry biomass plant^{-1}, 22.50% dry matter content, and 8.21 t ha^{-1} total yield. Compared to T2, T7 enhanced fresh biomass by 49.2%, dry biomass by 55.0%, dry matter content by 3.9%, and total yield by 65.9%. The highest N and K contents were found at T7 at 2.81% and 1.90%, whereas the lowest were recorded at T1 at 1.39% and 1.16%. For P, the highest content was observed at T5 at 1.91%, which was statistically similar to all other treatments except T1 at 1.56%. Significant ($p \leq 0.05$) differences were observed among treatments for HI, ANUE, and CIR (Table 5). The highest HI was recorded in treatment T7 at 55.41% ± 1.08%, while the lowest was observed in the negative control T1 at 28.96% ± 1.38%. ANUE also varied considerably among treatments. Treatment T7 exhibited the highest ANUE at 24.27 ± 0.62 g g^{-1}, whereas T1 showed negative efficiency −15.31 ± 0.94 g g^{-1}. Economic analysis revealed that T7 achieved the maximum CIR at 2.63 ± 0.07, followed by T5 (2.29 ± 0.08). The lowest CIR was recorded in T1 at 0.92 ± 0.08, while the positive control T2 attained a moderate CIR of 1.58 ± 0.06. Overall, T7 increased the CIR by 66.5% compared to the positive control T2.

TABLE 3 | Effects of biochar-based urea fertilizers on pod diameter, pod moisture content, number of branches, and root length of lady's finger.

Treatment	Pod diameter (cm)	Pod moisture content (%)	Branches plant^{-1}	Root length at 80 DAS (cm)
T1	3.93 ± 0.08^{d}	82.02 ± 0.83^{ab}	2.66 ± 0.34^{e}	21.89 ± 1.06^{ab}
T2	4.55 ± 0.10^{c}	80.83 ± 1.54^{b}	3.55 ± 0.19^{d}	20.14 ± 0.44^{b}
T3	4.60 ± 0.11^{c}	80.57 ± 1.94^{b}	3.00 ± 0.34^{e}	22.97 ± 1.10^{a}
T4	4.73 ± 0.13^{abc}	82.20 ± 0.56^{ab}	4.77 ± 0.20^{c}	20.52 ± 1.15^{b}
T5	4.66 ± 0.08^{bc}	83.85 ± 2.12^{a}	5.33 ± 0.33^{b}	23.70 ± 1.70^{a}
T6	4.83 ± 0.07^{ab}	82.81 ± 0.89^{ab}	5.55 ± 0.19^{ab}	22.05 ± 0.58^{ab}
T7	4.89 ± 0.09^{a}	82.15 ± 1.02^{ab}	5.89 ± 0.20^{a}	23.08 ± 1.19^{a}
Level of sig.	***	NS	***	*
CV (%)	2.09	4.25	6.18	5.11
LSD	0.170	0.836	0.479	1.987

Note: Here, all values are expressed as mean ± SD. Means followed by different superscript letters differ significantly at $p \leq 0.05$ according to Tukey's HSD test.
Significance levels: ***$p \leq 0.001$; *$p \leq 0.05$.
Abbreviations: CV, Coefficient of variation; NS, not significant.

TABLE 4 | Effects of biochar-based urea fertilizers on biomass production, dry matter content, and plant N, P, and K accumulation in lady's finger.

Treatment	Fresh biomass plant^{-1} (g)	Dry biomass plant^{-1} (g)	Dry matter content (%)	N (%) plant^{-1}	P (%) plant^{-1}	K (%) plant^{-1}
T1	56.62 ± 1.84^{e}	10.43 ± 0.56^{e}	18.41 ± 0.39^{e}	1.39 ± 0.13^{e}	1.56 ± 0.08^{b}	1.16 ± 0.13^{d}
T2	61.44 ± 1.06^{d}	13.82 ± 0.46^{c}	22.50 ± 1.06^{ab}	2.25 ± 0.10^{d}	1.77 ± 0.07^{a}	1.54 ± 0.15^{c}
T3	58.19 ± 2.04^{e}	12.30 ± 0.70^{d}	21.13 ± 0.94^{bc}	2.15 ± 0.09^{d}	1.81 ± 0.11^{a}	1.65 ± 0.06^{bc}
T4	68.32 ± 0.77^{c}	13.45 ± 0.31^{c}	19.69 ± 0.67^{de}	2.30 ± 0.13^{cd}	1.84 ± 0.12^{a}	1.72 ± 0.08^{abc}
T5	76.62 ± 1.56^{b}	16.89 ± 0.73^{b}	22.06 ± 1.05^{ab}	2.55 ± 0.09^{b}	1.91 ± 0.08^{a}	1.79 ± 0.13^{ab}
T6	70.75 ± 1.23^{c}	14.31 ± 0.39^{c}	20.23 ± 0.30^{cd}	2.46 ± 0.09^{bc}	1.82 ± 0.12^{a}	1.87 ± 0.10^{a}
T7	91.64 ± 1.03^{a}	21.42 ± 0.42^{a}	23.37 ± 0.20^{a}	2.81 ± 0.10^{a}	1.86 ± 0.11^{a}	1.90 ± 0.11^{a}
Level of sig.	***	***	***	***	*	***
CV (%)	2.12	3.69	3.62	4.78	5.85	6.77
LSD	2.579	0.954	1.344	0.192	0.185	0.199

Note: Here, all values are expressed as mean ± SD. Means followed by different superscript letters differ significantly at $p \leq 0.05$ according to Tukey's HSD test.
Significance levels: ***$p \leq 0.001$; *$p \leq 0.05$.
Abbreviation: CV, coefficient of variation.

TABLE 5 | Effects of biochar-based urea fertilizers on total yield, harvest index, agronomic nitrogen-use efficiency, economic return, and fruit pH of lady's finger.

Treatment	Total pod yield (t ha^{-1})	Harvest index (%)	Agronomic N-use efficiency (g g^{-1})	Cost-income ratio	Fruit pH
T1	4.78 ± 0.23^{f}	28.96 ± 1.38^{f}	-15.31 ± 0.94^{g}	0.92 ± 0.08^{f}	6.60 ± 0.10^{a}
T2	8.21 ± 0.16^{e}	45.87 ± 1.70^{de}	0.00 ± 0.00^{e}	1.58 ± 0.06^{e}	6.57 ± 0.06^{a}
T3	7.81 ± 0.37^{e}	44.09 ± 0.86^{e}	-1.74 ± 1.60^{f}	1.51 ± 0.09^{e}	6.53 ± 0.06^{a}
T4	9.17 ± 0.26^{d}	46.59 ± 1.67^{d}	4.34 ± 0.49^{d}	1.77 ± 0.08^{d}	6.60 ± 0.10^{a}
T5	11.84 ± 0.33^{b}	52.15 ± 0.95^{b}	16.32 ± 0.70^{b}	2.29 ± 0.08^{b}	6.63 ± 0.06^{a}
T6	10.18 ± 0.31^{c}	49.58 ± 1.50^{c}	8.89 ± 0.44^{c}	1.97 ± 0.06^{c}	6.63 ± 0.12^{a}
T7	13.62 ± 0.27^{a}	55.41 ± 1.08^{a}	24.27 ± 0.62^{a}	2.63 ± 0.07^{a}	6.53 ± 0.06^{a}
Level of sig.	***	***	***	***	NS
CV (%)	2.59	2.45	16.27	3.96	1.28
LSD	0.427	1.992	1.507	0.126	0.148

Note: Here, all values are expressed as mean ± SD. Means followed by different superscript letters differ significantly at $p \leq 0.05$ according to Tukey's HSD test.
Significance levels: ***$p \leq 0.001$.
Abbreviations: CV, Coefficient of variation; NS, not significant.

3.2 | Nutritional Quality Traits

Nutritional quality traits of lady's finger pod were significantly ($p \leq 0.05$) influenced by treatments, including TSS, TA, ascorbic acid, total phenolics, total flavonoids, and protein, while pH was unaffected (Table 5 and Figure 7). The pH of fruits ranged from 6.53 to 6.63, showing no significant ($p > 0.05$) variation among treatments (Table 5). TSS differed significantly ($p \leq 0.05$), with treatment T7 exhibiting the highest value at 7.26 °Brix, whereas the lowest was recorded in T1 at 5.53 °Brix. TA was highest in T7 at 0.282% and lowest in T1 at 0.194%. Similarly, treatment T7 produced the highest ascorbic acid content at 14.26 mg 100 g^{-1} Fw, total phenolics at 12.13 mg GAE g^{-1} Fw, total flavonoids at 3.45 mg CAE g^{-1}, and protein at 22.24 mg g^{-1} Fw. In contrast, treatment T1 showed the lowest values for ascorbic acid at 11.28 mg 100 g^{-1} Fw, total phenolics at 8.78 mg GAE g^{-1} Fw, total flavonoids at 2.26 mg CAE g^{-1}, and protein at 14.56 mg g^{-1} Fw.

3.3 | Pearson's Correlation Analysis

Pearson's correlation analysis revealed strong and statistically significant interrelationships between growth, physiological, yield, and quality attributes of lady's finger (Figure 8). Major vegetative growth and physiological traits, including number of leaves (NL), leaf area (LA), plant height (PH), photosynthesis rate (PR), and branches per plant (BPP), exhibited strong positive correlations with fresh biomass per plant (FBPP) and dry biomass per plant (DBPP), with correlation coefficients generally ranging from $r \approx 0.76$ to 0.94 ($p < 0.05$ to $p < 0.001$). These traits were also positively and significantly associated with total pod yield per hectare (TPYPH), ANUE, and HI, highlighting their combined contribution to yield formation and nitrogen utilization efficiency. Yield-related parameters, including FBPP, DBPP, pod length (PL), and individual pod weight (IPW), showed very strong positive intercorrelations ($r \approx 0.84$–0.95; $p < 0.01$ to $p < 0.001$), indicating that improvements in biomass accumulation and pod attributes directly translated into enhanced yield performance. Protein content was positively correlated with most biomass and yield traits, reflecting its dependence on improved assimilate production and NUE. Quality attributes such as TSS, ascorbic acid (AA), total phenolic content (TPC), and total flavonoids (TF) were positively correlated among themselves and showed moderate positive associations with yield and biomass traits, suggesting that higher productivity did not compromise pod quality. Dry matter (DM) content exhibited positive correlations with both yield and biochemical parameters, whereas pod moisture content (PMC) and pH showed weak to negative relationships with most yield and quality attributes. In contrast, days required for first flowering (DRFF) and days required for first pod harvest (DRFPH) were strongly and negatively correlated with growth, biomass, and yield traits (with correlation coefficients reaching up to $r \approx -0.99$; $p < 0.01$ to $p < 0.001$), indicating that delayed phenological development markedly reduced productivity. Overall, the correlation matrix clearly demonstrates that enhanced vegetative growth, photosynthetic efficiency, and NUE are closely linked with increased pod yield and improved quality, whereas delayed flowering and harvesting exert a pronounced negative influence on yield performance.

3.4 | PCA Biplot Interpretation

PCA was performed to understand the multivariate relationships among growth, physiological, yield, and quality traits (Figure 9). The PCA biplot shows that the first two principal components (PCs) explained 84.1% of the total variability, with PC1 accounting for 73.2% and PC2 accounting for 10.9% of the variation. PC1 was predominantly associated with vegetative

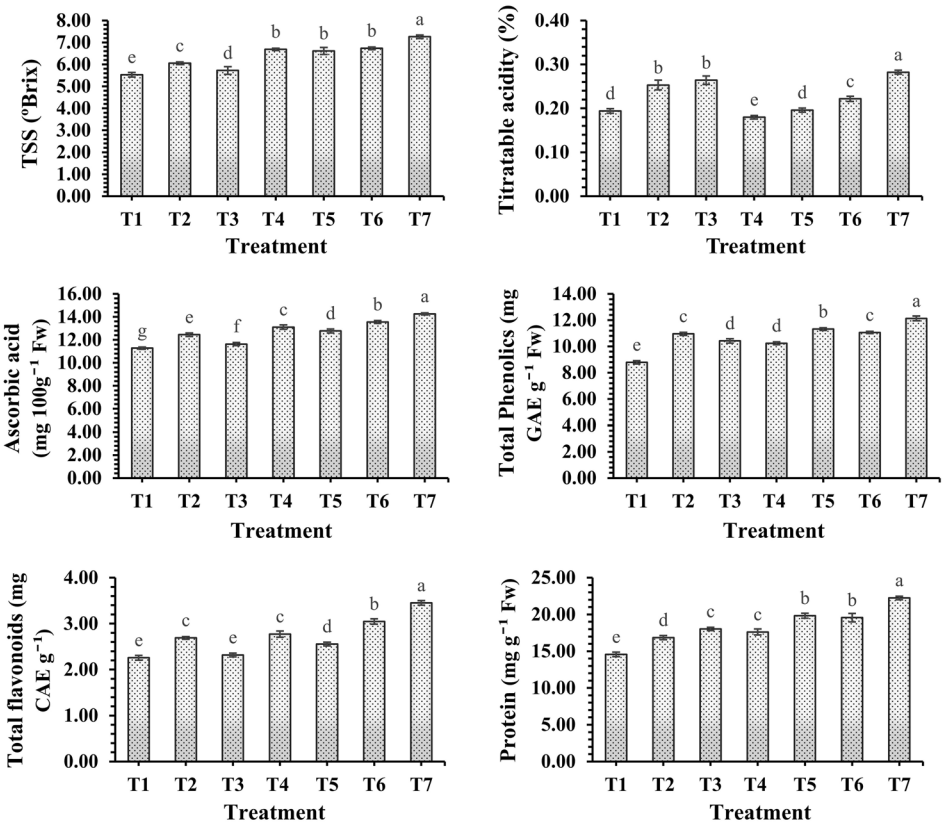


FIGURE 7 | Effects of biochar-based urea fertilizers on TSS, titratable acidity, ascorbic acid, total phenolics, total flavonoids, and protein content of lady's finger.

growth, biomass accumulation, yield attributes, and quality parameters. Positive loadings along PC1 were observed for number of leaves (NL), leaf area (LA), plant height (PH), plant stem diameter (PSD), photosynthesis rate (PR), branches per plant (BPP), fresh biomass per plant (FBPP), dry biomass per plant (DBPP), dry matter (DM), ANUE, HI, TSS, ascorbic acid (AA), total phenolic content (TPC), total flavonoids (TF), and protein content. This indicates a strong positive association among growth vigor, NUE, biomass production, and biochemical quality traits. Traits such as days required for first flowering (DRFF) and days required for first pod harvest (DRFPH) were positioned on the opposite side of PC1, indicating a negative association with growth, yield, and quality parameters, suggesting that early flowering and harvesting were linked with improved biomass and quality performance. PC2 contributed modestly to total variation and primarily separated treatments based on pod moisture content (PMC), pH, and TA indicating that these postharvest quality traits varied independently of the major growth and yield parameters represented by PC1. The treatment distribution revealed a clear grouping pattern. Treatments T7, T6, and T5 were positioned in the positive quadrant of PC1, closely associated with most growth, yield, nutrient efficiency, and quality traits, indicating superior overall performance.

4 | Discussion

Nitrogen (N) is an essential macronutrient required for plant growth, as it is a key component of amino acids, proteins, enzymes, and chlorophyll (Wang et al. 2024). Despite their importance, conventional N fertilizers have low use efficiency, with only 20%–40% of applied N absorbed by crops, leading to significant losses via leaching, volatilization, and denitrification (Govindasamy et al. 2023). In the present study, BBUFs significantly ($p \leq 0.05$) enhanced the growth, physiological performance, yield, and nutritional quality of lady's finger. The results of this study indicate that all BBUFs (T3-T7) significantly ($p \leq 0.05$) improved the vegetative growth of lady's finger compared with the conventional urea fertilizer (T2). Enhanced growth was reflected by increases in leaf number, leaf area, plant height, and stem diameter. Among the treatments, BCU (T7) produced the most substantial improvement, with 58.3% more leaves, a 17.0% increase in leaf area, 29.4% greater plant height, and a 21.8% larger stem diameter relative to traditional urea fertilizer (T2). These results suggest enhanced nutrient availability and improved nitrogen uptake efficiency. Notably, the increased stem diameter observed under both BMU (T6) and BCU (T7) indicates superior structural development, which likely facilitates more efficient water and nutrient transport, thereby supporting higher biomass accumulation and reproductive potential. These results are consistent with earlier studies showing that modified biochar-based slow-release fertilizers (BBSRFs) increased corn leaf area by 24.8% compared with chemical fertilizers (Khajavi-Shojaei et al. 2023), and biochar compound fertilizer enhanced spring wheat plant height by 4%–14% (Mikos-Szymańska et al. 2019).

Leaf development plays a crucial role in determining photosynthetic capacity and biomass accumulation, as an expanded

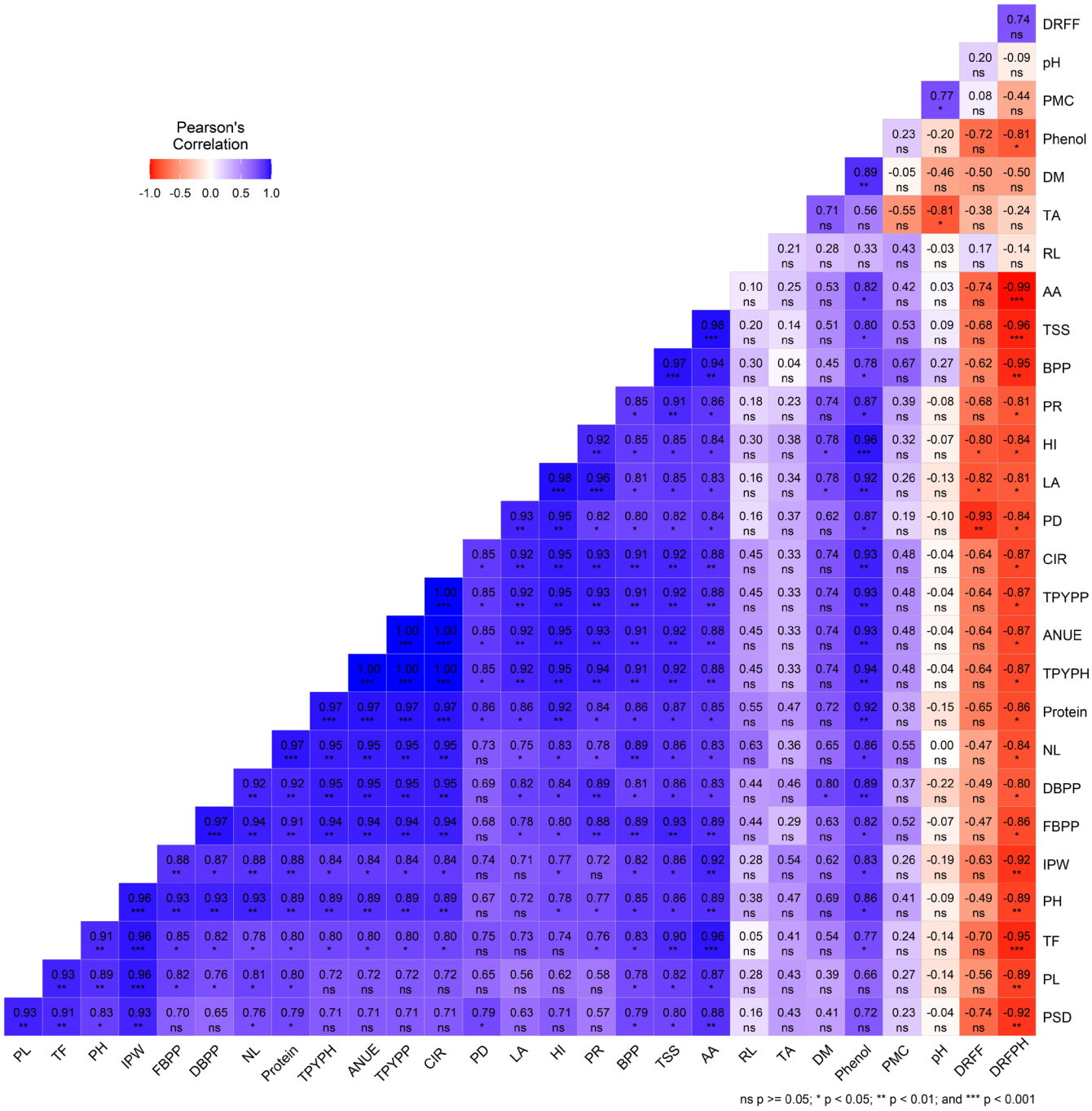


FIGURE 8 | Pearson correlation analysis among the studied parameters of lady's finger.

photosynthetically active surface area enhances light capture and carbon assimilation. In this study, the highest photosynthesis rate (13.21 μmol $m^{-2} s^{-1}$) was observed under BCU (T7) compared to other treatments. These results are consistent with Chen et al. (2021), who reported that a 20% reduction in chemical fertilizer combined with biochar did not significantly reduce crop yield or photosynthetic activity. Phenological traits were significantly influenced by treatment application, with earlier flowering and pod harvesting observed under BCU (T7) and BMU (T6). Accelerated phenological development is often linked to improved nutrient availability and hormonal regulation, facilitating efficient transition from vegetative to reproductive stages. The observed strong negative correlations between days to flowering or pod harvest and yield-related traits suggest that delayed phenology limits biomass accumulation and yield formation. These results are supported by Zhang et al. (2025), who demonstrated that BCU fertilizers enhanced nitrogen uptake, leading to improved plant growth and yield.

The results demonstrate that BBUFs significantly ($p \leq 0.05$) enhance pod development compared with conventional urea. Superior pod attributes recorded under BCU (T7), including higher individual pod weight (14.34 ± 0.32 g), pod length (12.97 ± 0.51 cm), and pod diameter (4.89 ± 0.09 cm), indicate more efficient assimilate allocation toward reproductive organs. Specifically, BCU increased pod weight, length, and

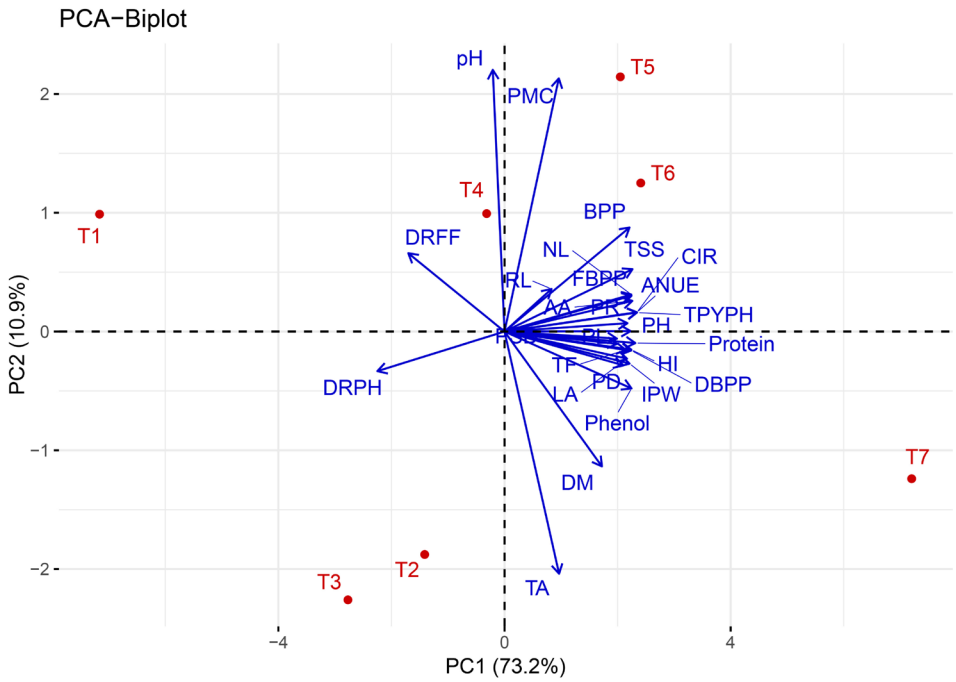


FIGURE 9 | PCA biplot showing associations among treatments and growth, yield, and quality attributes of lady's finger.

diameter by 34.0%, 29.9%, and 7.5% compared to conventional urea (T2). The BMU (T6) also exhibited notable improvements, albeit lower than BCU, suggesting that biochar incorporation enhances nutrient use efficiency and reproductive growth. Similar improvements in reproductive traits have been reported in maize, where BBFs increased ear length and diameter by 5.43% and 2.47%, respectively (Yin et al. 2022). Moreover, BBUFs significantly ($p \leq 0.05$) improved vegetative growth and root development relative to conventional urea. The greatest number of branches was observed under BCU (T7) at 5.89 ± 0.20 plant^{-1}, followed by BMU (T6), whereas urea (T2) produced only 3.55 ± 0.19 branches plant^{-1}. Similarly, Qaderi et al. (2025) reported that increased nitrogen absorption supports more efficient nutrient assimilation, resulting in stronger and more vigorous plants. Root growth was also enhanced under BBUFs, with the longest roots recorded in BMU (T5) at 23.70 cm, statistically comparable to BMU (T3) and BCU (T7), while the shortest roots occurred under conventional urea (T2) at 20.14 cm. These responses indicate that the biochar coating in BCU slowed early nutrient release and maintained nutrient availability at later growth stages. Similar benefits of biochar-based nitrogen fertilizers (BBNFs) have been widely reported, including increases in cotton root length (26% relative to NH_4Cl) and root biomass and volume (26% and 38% relative to urea), particularly under dryland and drought conditions (Wen et al. 2017; Shi et al. 2020; Bruun et al. 2014). In addition, BBNFs stimulate soil N cycling by increasing urease activity (~10%) and the abundance of key nitrifying and denitrifying microorganisms, including *Acidothermaceae, Sphingomonadaceae, Nitrospira, Nitrobacter*, etc., compared with urea fertilization (Liao et al. 2020; Shi et al. 2020; Wang et al. 2023).

The substantial increases in fresh and dry biomass and dry matter content observed under BBUFs indicate improved nitrogen uptake, assimilation, and conversion into plant biomass. Among treatments, BCU (T7) consistently outperformed others, producing 91.64 g fresh biomass plant^{-1}, 21.42 g dry biomass plant^{-1}, 23.37% dry matter content, and a total yield of 13.62 t ha^{-1}. In contrast, conventional urea (T2) resulted in 61.44 g fresh biomass plant^{-1}, 13.82 g dry biomass plant^{-1}, 22.50% dry matter content, and 8.21 t ha^{-1} yield. Relative to conventional urea, BCU increased fresh biomass by 49.2%, dry biomass by 55.0%, dry matter content by 3.9%, and total yield by 65.9%, demonstrating its superior agronomic efficiency. These findings align with previous studies showing that BBNFs markedly enhance crop biomass and yield. For instance, Xia et al. (2022) reported increases of 292% and 283% in fresh and dry maize biomass, respectively, compared with unfertilized controls, while Khajavi-Shojaei et al. (2023) observed a 24.2% increase in aboveground dry matter with modified BBSRF relative to chemical fertilizer. Similarly, Guo et al. (2025) documented yield and dry matter increases of 25.1% and 22.8% in vegetables under greenhouse conditions. The yield advantages of BBFs are primarily attributed to improved nitrogen retention, sustained nutrient release, long-term soil organic matter accumulation, and enhanced nitrogen availability during critical growth stages (Ali et al. 2025). Consistent yield improvements have also been reported in peanut (Gao et al. 2017), maize (Zheng et al. 2017; Puga et al. 2020), wheat (Mikos-Szymańska et al. 2019), and rice (An et al. 2022).

Significant differences ($p \leq 0.05$) among treatments in HI, NPK, ANUE, and CIR indicate distinct effects of fertilizer management on yield formation and economic performance. The highest HI was observed under BCU (T7) at $55.41\% \pm 1.08\%$, reflecting more efficient allocation of assimilates toward pod development rather than vegetative growth. This enhanced partitioning suggests improved synchronization between nitrogen availability and reproductive demand, which likely contributed to higher yield and NUE. In addition, BCU (T7) produced

the highest plant N (2.81%) and K (1.90%) contents, indicating enhanced nutrient uptake and utilization. ANUE also varied significantly among treatments, highlighting the critical role of nutrient management. In this study, BCU (T7) achieved the highest ANUE ($24.27 \pm 0.62\,g\,g^{-1}$), whereas T1 exhibited negative efficiency ($-15.31 \pm 0.94\,g\,g^{-1}$), indicating severe nitrogen limitation. The superior ANUE under BCU suggests enhanced nitrogen recovery and reduced losses, demonstrating both agronomic and environmental benefits. Low nitrogen use efficiency (NUE) in other treatments is primarily attributed to the lack of synchrony between fertilizer N availability and crop N demand. Previous studies have shown that approximately 60% of nitrogen from BBNFs can be retained in the soil, contributing to a more sustained nitrogen supply (Cen et al. 2021). Under equivalent fertilization rates, BBNFs have been reported to result in higher nitrogen uptake in oilseed rape compared with conventional urea (Jia et al. 2021). Consistently, BBFs have been shown to enhance nitrogen use efficiency by 14.5%–242.5% relative to chemical nitrogen fertilizers (Puga et al. 2020; Zhou et al. 2021; Zhao et al. 2022). The improved physiological efficiency under BBUFs was reflected in superior economic performance. BCU (T7) achieved the highest CIR at 2.63 ± 0.07, followed by T5 at 2.29 ± 0.08, whereas conventional urea (T2) recorded a comparatively lower CIR at 1.58 ± 0.06. The higher profitability of BCU is associated with improved NUE and reduced fertilizer input requirements. Consistent with these findings, BBNFs require less nitrogen per unit grain production ($58\,kg\,N\,t^{-1}$) than conventional inorganic fertilizers ($85\,kg\,N\,t^{-1}$), leading to higher profitability and lower environmental nitrogen losses (Zheng et al. 2017).

Beyond yield enhancement, BBUFs significantly improved the nutritional quality attributes of lady's finger, including TSS, TA, ascorbic acid, phenolics, flavonoids, and protein content without affecting fruit pH. Enhanced levels of ascorbic acid (14.26 mg $100\,g^{-1}$ Fw), total phenolics (12.13 mg GAE g^{-1} Fw), total flavonoids (3.45 mg CAE g^{-1} Fw), and protein ($22.24\,mg\,g^{-1}$ Fw) in BCU (T7) demonstrate a substantial improvement in both antioxidant capacity and nutritional value. These improvements may be attributed to the favorable nutrient availability and enhanced metabolic activity under BCU fertilizer, which likely promoted secondary metabolite synthesis. Similar improvements in quality have been reported in sugar beet, where BBFs increased both yield and sugar content (Chen et al. 2022). Moreover, the higher protein content observed under BCU ($14.56\,mg\,g^{-1}$) is closely associated with improved NUE, indicating that enhanced nitrogen assimilation directly promotes protein biosynthesis in pods. Pearson's correlation analysis and PCA provided robust multivariate confirmation of treatment effects. Strong positive correlations among vegetative growth, photosynthetic activity, biomass accumulation, yield, and quality traits indicate the integrated regulation of plant productivity. In contrast, the negative association of delayed flowering and harvesting with yield underscores the importance of early phenological development for maximizing productivity. The PCA biplot clearly distinguished treatments based on overall performance, with T7, T6, and T5 clustering in the positive region of PC1, which was strongly influenced by growth vigor, NUE, yield, and quality attributes.

Overall, BCU significantly ($p \leq 0.05$) improved both yield and quality of lady's finger compared with conventional urea. Although BMU also performed better than conventional urea, BCU consistently produced the best results. This superiority can be attributed to the physical encapsulation of urea by biochar, which enables a slow and synchronized release of nitrogen. Supporting this mechanism, Jia et al. (2021) reported that replacing urea with BBNFs reduced total soil nitrogen loss by approximately 30% and decreased cumulative NO_3^- leaching by 25%. NH_3 emissions from agriculture account for nearly 90% of global NH_3 emissions (Brentrup et al. 2000), posing serious environmental risks as NH_3 contaminates aquatic ecosystems (Park et al. 2019), acts as an indirect greenhouse gas, and contributes to near-surface ozone formation (Ravishankara et al. 2009; Ma et al. 2021). The use of BBNFs has been shown to significantly mitigate these emissions, with NH_3 volatilization reduced by up to 50% compared with conventional urea (González-Cencerrado et al. 2020). In addition, cumulative N_2O emissions were reported to decrease by 8% (Puga et al. 2020) and up to 40% (Qian et al. 2014) under BBNF application. These reductions are likely associated with a lower abundance of soil denitrifiers under BBNF treatments relative to urea, thereby suppressing denitrification-driven N_2O production (Liao et al. 2020). These findings demonstrate that BCU not only enhances crop productivity and quality but also offers substantial environmental benefits by improving nitrogen retention and reducing reactive nitrogen losses.

5 | Conclusion

This study demonstrates that BBNFs, particularly BCU, represent an effective and sustainable nitrogen management strategy for lady's finger production. Among all treatments, BCU consistently outperformed conventional urea and BMU formulations by significantly enhancing vegetative growth, photosynthetic activity, biomass accumulation, and pod yield. The substantial yield increase (65.9% over conventional urea) was accompanied by marked improvements in ANUE, HI, and economic returns. Beyond yield enhancement, BCU significantly improved the nutritional quality attributes of lady's finger, including TSS, ascorbic acid, phenolics, flavonoids, and protein content. The superior performance of BCU can be attributed to the biochar coating, which facilitates slow and synchronized nitrogen release, enhances nitrogen retention in soil, and minimizes losses through volatilization and leaching. Consequently, BCU not only improves crop productivity and profitability but also offers significant environmental benefits by reducing reactive nitrogen losses and associated ecological risks. To achieve optimum results, integrated pest management and further multi-location studies are recommended to validate these benefits across diverse agroecological conditions.

Author Contributions

Litun Ahmed Labib: conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review and editing, formal analysis, supervision, data curation, resources. **Md. Lotifuzzaman Lemon:** investigation, formal analysis, data curation, writing – original draft. **Most. Sanjida Badhon:** formal analysis, investigation, data curation, writing – original draft. **Md. Sakil Ahmmed:** investigation, formal analysis, data curation, writing – original draft. **Md. Masum Reza:** investigation, formal analysis, data

curation, writing – original draft. **Md. Rifatul Islam Rifat:** formal analysis, data curation, investigation. **Swagata Ahmed:** conceptualization, investigation, writing – review and editing, validation, formal analysis, methodology, data curation, visualization, writing – original draft. **Md. Zahir Rayhan:** conceptualization, investigation, writing – original draft, visualization, validation, formal analysis, resources, data curation, methodology.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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