



RESEARCH ARTICLE

Optimising sugarcane biochar and nutrient management on growth and productivity of spring maize under trans-Gangetic plains of Punjab

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Abstract

A field experiment was conducted during the spring season of 2024–25 at the Agricultural Research Farm, Lovely Professional University, Punjab, to evaluate the optimisation of sugarcane straw biochar rate and nutrient management on spring maize (*Zea mays* L.). The trial was laid out in a split-plot design (SPD) with 3 replications. The main plot received three different treatment levels of sugarcane biochar rate which included 5 t ha⁻¹ (M₁) and 10 t ha⁻¹ (M₂) and 15 t ha⁻¹ (M₃). Similarly, 4 treatments were selected for the subplot section, consisting of S₁ for absolute control, S₂ for 100 % recommended dose of nitrogen and phosphorus (RDNP), S₃ for 50 % RDNP with nano di-ammonium phosphate (nano DAP) and S₄ for 50 % RDNP with liquid nutrient foliar sprays. Results revealed that, M₃ achieved the significantly highest plant height of 221.46 cm during harvest while also reaching the highest dry matter accumulation (DMA) of 230.06 g plant⁻¹ and soil plant analysis development (SPAD) index of 45.53 which resulted in a 31.8 % grain yield increase compared to M₁. The evaluation of different nutrient conditions showed that S₂ and S₃ performed equally well for all measured characteristics when compared to S₁. Under the S₂ treatment, both plant height and grain yield increased by 28.1 %, while yield attributes also showed improvement. The interaction showed distinct patterns because M₃S₂ achieved significantly highest growth and yield of spring maize. The maximum chlorophyll index (46.80), grain yield (57.03 q ha⁻¹) and straw yield (75.03 q ha⁻¹) were found in M₃S₂ which are statistically at par with M₃S₃ and M₃S₄. The combination of reduced fertiliser application with foliar treatment produced better crop results when biochar usage reached its peak level. Therefore, integrating sugarcane biochar with optimised nutrient level offers a pragmatic pathway for improving growth and productivity of spring maize in Punjab.

Keywords: chlorophyll index; growth and productivity; liquid nutrient; nano di-ammonium phosphate; soil amendment; spring maize; sugarcane straw biochar; yield attributes

Introduction

Rapid population growth, diminishing arable land, escalating input costs and shifting climatic patterns collectively threaten global food security. In cereal-based cropping systems, these pressures frequently translate into yield stagnation and declining resource-use efficiency, particularly in low-organic-matter soils where conventional fertilisation results in substantial nutrient losses (1, 2). Maize (*Zea mays* L.) is one of the major cereal crops cultivated across diverse agro-ecologies but ensuring sustainable maize production under increasing climatic and edaphic pressures requires modifications to management practices that enhance soil quality, improve nutrient-use efficiency and support the physiological functioning of the maize (3). This challenge has generated considerable interest in carbon-based soil amendments and precision nutrient management strategies that work synergistically to stabilise yields while reducing environmental footprint. Biochar is a carbon rich, porous material commonly produced through the pyrolysis of biomass and is regarded as a promising soil amendment

with the potential to improve soil physical structure, water retention and nutrient dynamics. The long-term field data points towards the possible effect of biochar to improve the growth and productivity of maize by promoting growth in height and biomass accumulation and physiological characteristics of plants, although responses vary considerably depending on soil type, biochar feedstock, application rate and background fertility status (3, 4). Besides promoting short-term growth, yield benefits of biochar have been also determined to be sustainable over years, including through the improved retention of moisture and nutrient and therefore long-term cereal system productivity has also been proposed.

Studies have demonstrated that the co-application of biochar with mineral fertilisers enhances soil nitrogen retention and nitrogen uptake in maize, leading to measurable yield gains and reduced nitrogen losses (5). This is particularly relevant in intensively managed maize systems across South Asia, where improving nutrient-use efficiency is critical for reducing production costs and minimising environmental externalities. Recent advances in nano-

fertiliser technology and foliar nutrient delivery have opened new avenues for precision nutrition management. Nano-scale products, owing to their high surface area, facilitate enhanced leaf absorption and timely delivery of nutrients during critical crop growth stages. Foliar application of nano di-ammonium phosphate (nano DAP), timed to coincide with vegetative and reproductive growth stages, has been shown to sustain chlorophyll content, assimilate production and grain filling. Research indicates that nano DAP supplementation of reduced basal fertilisation can maintain maize growth and yield attributes, suggesting that foliar nano-phosphorus interventions hold real potential to complement conventional soil fertility programmes (6). Rather than replacing soil-applied fertilisers, nano-inputs serve as targeted supplements that enhance nutrient-use efficiency in systems aiming to reduce basal input levels without compromising crop performance (7).

However, two knowledge gaps regarding biochar remain. Firstly, its agronomic behaviour is highly contextual; findings from one soil-climatic situation may not necessarily be applicable to another and, therefore, require local field validation. Secondly, integrated field results comparing different biochar application rates with alternative nutrient management strategies, particularly reduced basal nutrient doses combined with foliar supplements administered to improve nutrient-use efficiency, are limited. Addressing these gaps is especially important in maize-based systems of Punjab, where ensuring yield stability under increasing climatic variability demands soil amendment strategies that simultaneously improve moisture buffering and nutrient retention while supporting the overall physiological health of the crop.

The present study was, therefore, designed to evaluate the optimum rate of sugarcane straw biochar in combination with different nutrient management strategies and to assess their interactive effects on the growth, agro-physiological performance and productivity of spring maize. The findings are intended to provide field-validated recommendations for biochar-integrated nutrient management in spring maize and to contribute to sustainable intensification goals, particularly in agro-ecological zones where improved nutrient-use efficiency, yield stability and climate resilience are increasingly necessary.

Materials and Methods

The field experiment was conducted at the Agricultural Research Farm of Lovely Professional University (LPU), Punjab, India, during the spring season of 2024–25 under open-field conditions. This field

has an average elevation of 252 m mean sea level and is located at 31°22'31.81" North latitude and 75°23'03.02" East longitude. The experimental site in Punjab (central plain/trans-Gangetic agro-climatic region) experienced a typical spring-season climate, characterised by rapidly rising temperatures, high pre-monsoon heat and limited erratic rainfall. Weekly weather data (rainfall, temperature, relative humidity and pan evaporation) were recorded at the automated weather station of LPU, Phagwara, throughout the cropping period (8, 9). The experimental soil was sandy loam in texture (sand 75.0 %, silt 10.3 %, clay 14.7 %), derived from Indo-Gangetic alluvium. Pre-sowing soil analysis (0–30 cm depth) revealed a slightly alkaline reaction (pH 7.92), normal electrical conductivity (EC 0.32 dS m⁻¹), low organic carbon (0.31 %), low available nitrogen (185 kg ha⁻¹), medium available phosphorus (22.7 kg ha⁻¹) and medium available potassium (175.2 kg ha⁻¹). The gross plot size was 5 × 4 m (20.0 m²) and the net plot size was 4.4 × 3.4 m (14.96 m²). The experiment was carried out in split-plot design (SPD) replicated thrice with sugarcane straw biochar at 5 t ha⁻¹ (M₁), 10 t ha⁻¹ (M₂) and 15 t ha⁻¹ (M₃) formed the main-plot factor (M). The subplot factor (S) was nutrient-management strategies: S₁, control (zero nutrient); S₂, 100 % recommended dose of nitrogen and phosphorus (RDNP); S₃, 50 % RDNP, two foliar sprays of liquid nutrient at 20 and 50 days after sowing (DAS); and S₄, 50 % RDNP, two foliar sprays of liquid organic nutrient at 20 and 50 DAS (Table 1). The recommended dose of nutrients was 120 : 60 : 0 kg N : P₂O₅ : K₂O ha⁻¹. In S₂, nitrogen was applied in two equal splits: the first half (60 kg N ha⁻¹) as basal application at sowing and the remaining half as top-dressing at the knee-height stage; the entire recommended dose of phosphorus (60 kg P₂O₅ ha⁻¹) was applied basally. In S₃ and S₄, 50 % RDNP (60 kg N ha⁻¹ + 30 kg P₂O₅ ha⁻¹) was applied as basal dose. S₃ received two foliar sprays of nano DAP (TAG Nano NPK, Sunantha Organic Farms, Karnataka, India) at the recommended concentration, while S₄ received two foliar sprays of liquid organic nutrient at 10 mL L⁻¹ of water. Potassium was not applied, as the experimental soil had a medium potassium status. The test crop was spring maize (*Z. mays*), variety DKC 9208 and the crop was established on flatbeds using a spacing of 60 cm × 20 cm (row-to-row × plant-to-plant). Seeds were treated with Bavistin (carbendazim) at 4 g kg⁻¹ before sowing to protect against soil-borne fungal diseases. Irrigation was applied uniformly to all plots at critical growth stages (sowing, establishment, knee-height, tasseling and grain-filling), with subsequent irrigations at approximately 10–15-day intervals based on prevailing soil moisture conditions. Sugarcane straw biochar was produced through pyrolysis of sugarcane straw under limited oxygen conditions at a temperature of 400–600 °C. Prior to application, the biochar was ground and sieved

Table 1. Details of all the treatment combinations

Sl. No.	Treatment	Details
M ₁ S ₁	Sugarcane straw biochar at 5 t ha ⁻¹ + control (zero nutrient)	Spring maize (DKC 9208) was grown on flatbed with a spacing of 60
M ₁ S ₂	Sugarcane straw biochar at 5 t ha ⁻¹ + 100 % RDNP	Spring maize was grown at 60 × 20 cm spacing on flatbed
M ₁ S ₃	Sugarcane straw biochar at 5 t ha ⁻¹ + 50 % RDNP + nano DAP foliar	Spring maize was grown at 60 × 20 cm spacing on flatbed
M ₁ S ₄	Sugarcane straw biochar at 5 t ha ⁻¹ + 50 % RDNP + liquid nutrient	Spring maize was grown at 60 × 20 cm spacing on flatbed
M ₂ S ₁	Sugarcane straw biochar at 10 t ha ⁻¹ + control (zero nutrient)	Spring maize was grown on flatbed at 60 × 20 cm spacing
M ₂ S ₂	Sugarcane straw biochar at 10 t ha ⁻¹ + 100 % RDNP	Spring maize was grown on flatbed at 60 × 20 cm spacing
M ₂ S ₃	Sugarcane straw biochar at 10 t ha ⁻¹ + 50 % RDNP + nano DAP	Spring maize was grown at 60 × 20 cm spacing. Sugarcane straw
M ₂ S ₄	Sugarcane straw biochar at 10 t ha ⁻¹ + 50 % RDNP + liquid nutrient	Spring maize was grown at 60 × 20 cm spacing. Sugarcane straw
M ₃ S ₁	Sugarcane straw biochar at 15 t ha ⁻¹ + control (zero nutrient)	Spring maize was grown on flatbed at 60 × 20 cm spacing
M ₃ S ₂	Sugarcane straw biochar at 15 t ha ⁻¹ + 100 % RDNP	Spring maize was grown at 60 × 20 cm spacing on flatbed
M ₃ S ₃	Sugarcane straw biochar at 15 t ha ⁻¹ + 50 % RDNP + nano DAP	Spring maize was grown at 60 × 20 cm spacing. Sugarcane straw
M ₃ S ₄	Sugarcane straw biochar at 15 t ha ⁻¹ + 50 % RDNP + liquid nutrient	Spring maize was grown at 60 × 20 cm spacing. Sugarcane straw

RDNP: recommended dose of nitrogen and phosphorus; DAS: days after sowing.

to obtain particles of uniform size and characterised for pH, EC, total carbon content and surface area. Biochar was broadcast uniformly over respective main plots one week before sowing and incorporated into the surface soil (0–15 cm depth) by light harrowing, following standard agronomic practice for soil amendment application. To determine the relative chlorophyll status and assess the relative status of nitrogen nutrition and canopy vigour, the soil plant analysis development (SPAD) chlorophyll index was measured using fully expanded representative leaves with a SPAD metre (10, 11). Dry matter accumulation (DMA; g plant⁻¹) was calculated by weighing sampled plant material after oven drying until a constant mass was attained (12).

Statistical analysis

Data analysis and interpretation were conducted using Fisher's analysis of variance (ANOVA), as described by Gomez and Gomez (13). The least significant difference (LSD) test at a significance level of $\alpha \leq 0.05$, using OP STAT statistical software (13, 14).

Results and Discussion

Growth parameters of spring maize

Sugarcane straw biochar level

The growth parameters revealed that sugarcane biochar levels significantly influenced spring maize growth and physiological functioning (Table 2). At harvest, the tallest plants were recorded in the M₃ treatment (15 t ha⁻¹) (221.46 cm), followed by M₂ (10 t ha⁻¹) (212.62 cm), whereas the lowest plant height was observed in M₁ (198.25 cm). A similar trend was observed for chlorophyll status, where the maximum SPAD index occurred under M₃ (45.53) and M₂ (44.50) and the minimum under M₁ (41.18). Importantly, DMA increased markedly with biochar rate, reaching 230.06 g plant⁻¹ in M₃, followed by 223.43 g plant⁻¹ in M₂, while the lowest DMA was recorded in M₁ (200.84 g plant⁻¹). The concurrent increase in plant height, SPAD and DMA under higher biochar rates can be attributed to dose-dependent improvements in soil physico-chemical conditions. Higher biochar rates (15 t ha⁻¹) progressively increase soil cation exchange capacity (CEC) and water-holding capacity, creating a more stable, nutrient-rich rhizosphere that enhances root activity, chlorophyll synthesis and sustained photosynthetic efficiency across growth stages. These improvements in root-zone buffering translated into stronger assimilate production and biomass partitioning (15), consistent with evidence that biochar at higher incorporation rates proportionally improves soil structure, nutrient retention and crop physiological activity in maize. The observation that M₃ consistently outperformed M₁ and M₂ across all growth traits aligns with the dose-dependent CEC response documented for sugarcane straw biochar in alluvial soils. These responses are consistent with earlier evidence that biochar improves soil physical properties, increases nutrient retention and supports improved crop physiological activity, ultimately translating into higher biomass and growth in maize.

Nutrient management

Nutrient management practices significantly enhanced growth attributes compared with the control (Table 2). The highest plant height was recorded under S₂ (215.90 cm), which remained statistically comparable with S₃ (215.44 cm) and S₄ (214.94 cm), whereas the lowest height occurred under S₁ (196.82 cm). A similar response was observed in SPAD values, with the maximum indices

recorded under S₂ (44.94) and S₃ (44.71), while S₁ remained lowest (41.00). Dry matter accumulation also followed the same trend, being highest in S₂ (225.19 g plant⁻¹) and statistically at par with S₃ (224.61 g plant⁻¹), whereas S₁ recorded the minimum biomass (198.70 g plant⁻¹). These findings indicate that adequate nutrient availability, particularly when supported by foliar supplementation, maintains leaf chlorophyll content and strengthens photosynthetic activity, resulting in improved biomass accumulation and canopy vigour (16).

Interaction

The interaction between sugarcane straw biochar levels and nutrient management significantly influenced maize growth and the most pronounced responses occurred when higher sugarcane straw biochar was combined with improved nutrient supply (Table 2). The maximum plant height and DMA were recorded under M₃S₂ (227.03 cm and 236.90 g plant⁻¹), which remained closely comparable with M₃S₃ (226.47 cm and 236.53 g plant⁻¹) and M₃S₄ (226.27 cm and 235.90 g plant⁻¹), indicating that at high sugarcane straw biochar rates, reduced basal fertilisation supplemented by foliar nutrients could sustain vegetative growth and biomass formation nearly equal to full RDNP. Similarly, SPAD index peaked in M₃S₂ (46.80) and was statistically comparable with M₃S₃ (46.40), reflecting improved chlorophyll maintenance under enhanced nutrient availability and retention. Conversely, M₁S₁ recorded the lowest plant height (187.43 cm), SPAD (39.20) and DMA (186.63 g plant⁻¹), confirming that low sugarcane straw biochar coupled with nutrient omission restricts chlorophyll formation, assimilate supply and biomass production. Overall, the interaction pattern supports the explanation that sugarcane straw biochar strengthens fertiliser response by improving nutrient retention and root uptake, while foliar nutrient supplementation enhances nutrient-use efficiency, thereby sustaining chlorophyll status and dry matter production even under reduced basal fertilisation (17, 18).

100-grain weight, grain and straw yield

Sugarcane straw biochar levels

Sugarcane straw biochar levels significantly affected yield attributes and grain productivity of spring maize (Table 2). M₃ (37.44 g), M₂ (34.92 g) and M₁ (32.24 g) recorded the highest, middle and lowest test weight respectively (Table 2). Similarly, the number of grains per row was also increase steadily with the rate of sugarcane straw biochar, with M₃ (36.42) yielding the highest value, the next (34.42) followed by the lowest (30.00) in M₂ and M₁ respectively. These improvements in yield components translated into significantly higher productivity, with M₃ recorded a significantly higher grain yield of 54.05 q ha⁻¹, followed by M₂ (50.78 q ha⁻¹) and M₁ (41.01 q ha⁻¹). The same trend was observed for straw yield, which was highest in M₃ (74.05 q ha⁻¹), followed by M₂ (72.07 q ha⁻¹) and lowest in M₁ (69.14 q ha⁻¹). The yield advantage at higher biochar rates can be attributed to improved soil nutrient retention, increased water-holding capacity and enhanced assimilate supply to the sink, which collectively supported superior grain filling and biomass partitioning. Similar yield responses to biochar application in combination with fertiliser inputs have been consistently reported in maize production systems (19, 20).

Nutrient management

Nutrient management significantly influenced 100 seed weight, grains per row and yield (Table 2). The maximum 100 seed weight was recorded under S₂ (36.10 g), which was statistically comparable

Table 2. Effect of sugarcane straw biochar and nutrient management on growth and productivity of maize

Treatment	Plant height (cm)	DMA (g plant ⁻¹)	SPAD index	Number of grains per row (No.)	Test weight (100 seeds) (g)	Grain yield (q ha ⁻¹)	Straw yield (q ha ⁻¹)
Sugarcane straw biochar (M)							
M ₁	198.25 ^c	200.84 ^c	41.18 ^b	30.00 ^c	32.24 ^c	41.01 ^c	69.14 ^c
M ₂	212.62 ^b	223.43 ^b	44.45 ^a	34.42 ^b	34.92 ^b	50.78 ^b	72.07 ^b
M ₃	221.46 ^a	230.06 ^a	45.53 ^a	36.42 ^a	37.44 ^a	54.05 ^a	74.05 ^a
SEm (±)	0.15	0.34	0.14	0.13	0.17	0.15	0.07
C.D (p = 0.05)	0.60	1.36	0.56	0.51	0.67	0.61	0.29
Nutrient management (S)							
S ₁	196.82 ^c	198.70 ^c	41.00 ^c	29.83 ^c	32.03 ^c	40.43 ^c	68.64 ^d
S ₂	215.90 ^a	225.19 ^a	44.88 ^a	35.44 ^a	36.10 ^a	51.79 ^a	73.09 ^a
S ₃	215.44 ^{ab}	224.61 ^a	44.71 ^a	35.00 ^a	35.83 ^{ab}	51.36 ^a	72.82 ^{ab}
S ₄	214.94 ^b	223.94 ^b	44.29 ^b	34.11 ^b	35.50 ^b	50.89 ^b	72.47 ^{bc}
SEm (±)	0.24	0.32	0.14	0.21	0.15	0.21	0.12
CD (p = 0.05)	0.72	0.96	0.43	0.62	0.46	0.63	0.37
Interaction (M × S)							
M ₁ S ₁	187.43 ^f	186.63 ^f	39.20 ^g	27.33 ^g	30.07 ^d	35.67 ^f	65.58 ^l
M ₁ S ₂	202.30 ^d	206.00 ^d	42.23 ^{de}	31.67 ^{de}	33.10 ^c	43.37 ^d	70.67 ^h
M ₁ S ₃	202.00 ^d	205.83 ^d	41.83 ^e	31.33 ^e	32.93 ^c	42.70 ^d	70.37 ^{hi}
M ₁ S ₄	201.27 ^d	204.90 ^d	41.47 ^{ef}	29.67 ^f	32.87 ^c	42.30 ^d	69.93 ^{ij}
M ₂ S ₁	196.93 ^e	198.57 ^e	40.83 ^f	29.67 ^f	31.67 ^c	39.57 ^e	68.67 ^k
M ₂ S ₂	218.37 ^b	232.67 ^b	45.80 ^{bc}	36.67 ^b	36.37 ^b	54.97 ^b	73.57 ^d
M ₂ S ₃	217.87 ^b	231.47 ^b	45.90 ^{bc}	36.00 ^{bc}	36.03 ^b	54.60 ^b	73.23 ^{de}
M ₂ S ₄	217.30 ^b	231.03 ^b	45.47 ^c	35.33 ^c	35.60 ^b	54.00 ^b	72.80 ^{ef}
M ₃ S ₁	206.10 ^c	210.90 ^c	42.97 ^d	32.67 ^d	34.37 ^b	46.05 ^c	71.67 ^g
M ₃ S ₂	227.03 ^a	236.90 ^a	46.80 ^a	38.00 ^a	38.83 ^a	57.03 ^a	75.03 ^a
M ₃ S ₃	226.47 ^a	236.53 ^a	46.40 ^{ab}	37.67 ^a	38.53 ^a	56.77 ^a	74.85 ^{ab}
M ₃ S ₄	226.27 ^a	235.90 ^a	45.93 ^{bc}	37.33 ^a	38.03 ^a	56.37 ^a	74.67 ^{abc}

Means within a column followed by the same letters are not significantly different at $p \leq 0.05$ (LSD test). SPAD: soil plant analysis development; DMA: dry matter accumulation; SEm: standard error of mean; CD: critical difference.

with S₃ (35.83 g) and superior to the control S₁ (32.03 g). Similarly, the number of grains per row was greatest under S₂ (35.44) and S₃ (35.00), whereas the control remained the lowest (29.89). The highest grain yield was recorded in S₂ (51.79 q ha⁻¹), which was statistically at par with S₃ (51.36 q ha⁻¹), while the control produced the minimum grain yield (40.43 q ha⁻¹). A similar trend was observed for straw yield, with the highest values under S₂ (73.09 q ha⁻¹) and S₃ (72.82 q ha⁻¹) compared with the control (68.64 q ha⁻¹). These results demonstrate that both S₂ and S₃ effectively sustained yield formation, indicating that 100 % RDNP and 50 % RDNP supplemented with foliar nano DAP performed equally well. This underscoring the ability of nano-nutrient foliar application to maintain nutrient availability during reproductive growth and improve overall nutrient-use efficiency (21, 22).

Interaction effect (M × S)

The interaction analysis revealed that yield benefits were maximised when high biochar rates were combined with adequate nutrient supply (Table 2). Under M₃S₂, the maximum test weight (38.83 g), grains per row (38.00) and grain yield (57.03 q ha⁻¹) were recorded, outperforming all other treatment combinations. Straw yield also peaked in M₃ nutrient supported treatments, with M₃S₂ producing 75.03 q ha⁻¹, followed closely by M₃S₃ (74.85 q ha⁻¹) and M₃S₄ (74.67 q ha⁻¹). In contrast, the minimum performance was consistently recorded under M₁S₁, with the lowest grains per row (27.33), lowest test weight (30.07 g) and lowest grain yield (35.67 q ha⁻¹). These results indicate a clear synergy, whereby biochar-mediated improvements in soil nutrient retention enhanced the response to applied fertilisers, resulting in stronger sink formation and improved grain filling. Notably, the highest rate of sugarcane straw biochar (M₃) supplemented with foliar nano DAP (S₃) were still very competitive to the full RDNP (S₂), indicating that higher nutrient-

use efficiency can be achieved without significant yield loss through optimised soil amendment and nutrient supply (23, 24).

Relationship between growth and yield attributes with grain and straw yield of maize

The influence of sugarcane straw biochar and nutrient levels showed significant correlations with crop growth and development, yield attributes and productivity of maize during 2024–25 (Fig. 1). Growth parameters such as plant height ($r = 0.988$ and 0.980), DMA ($r = 0.998$ and 0.970), SPAD ($r = 0.997$ and 0.970) as well as yield attributes such as number of grains per row ($r = 0.991$ and 0.975) and test weight ($r = 0.972$ and 0.977) showed significant positive correlations ($p < 0.01$ and $p < 0.05$) with grain and straw yield of maize respectively (25). The uniformly strong correlations reflect the well-structured treatment gradient, where progressively increasing biochar rates consistently improved root-zone conditions and nutrient availability, resulting in proportional improvements across all measured growth and yield parameters.

Conclusion

Both sugarcane straw biochar rate and nutrient management strategy significantly influenced the growth, agro-physiological performance and yield of spring maize under trans-Gangetic plain conditions. Among the biochar rates, the application of 15 t ha⁻¹ sugarcane straw biochar consistently produced the best crop performance, as reflected in superior plant height, leaf chlorophyll status and dry matter accumulation (DMA). Among the nutrient management treatments, 100 % recommended dose of nitrogen and phosphorus (RDNP) recorded the highest overall performance; however, it was statistically comparable to 50 % RDNP supplemented with two foliar sprays of nano di-ammonium phosphate (nano DAP),

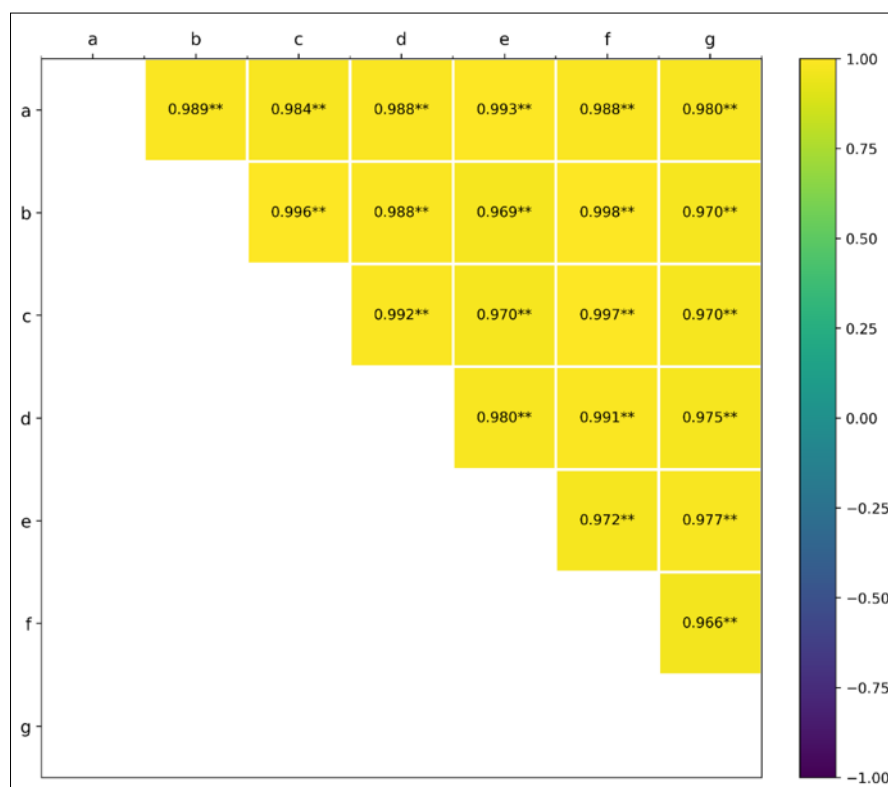


Fig. 1. Relationship between growth and yield attributes with grain and straw yield of spring maize. *Significant at $p \leq 0.05$; **significant at $p \leq 0.01$. (a) plant height; (b) dry matter accumulation (DMA); (c) soil plant analysis development (SPAD); (d) No. of grains per row; (e) test weight; (f) grain yield; (g) straw yield.

indicating that nano-nutrient foliar application can sustain crop productivity at reduced basal fertiliser levels, thereby improving nutrient-use efficiency and lowering input costs. The combination of 15 t ha⁻¹ sugarcane straw biochar and 100 % RDNP yielded the highest values for key characteristics such as test weight, number of grains per row, grain yield and straw yield and treatments of 15 t ha⁻¹ sugarcane straw biochar combined with 50 % RDNP and foliar nano DAP sprays were closely competitive, confirming the agronomic viability of this reduced-input strategy. The study therefore recommends integrating sugarcane straw biochar at 15 t ha⁻¹ with 50 % RDNP and two nano DAP foliar sprays as a practically viable and environmentally sound approach for enhancing spring maize productivity across the trans-Gangetic plains of Punjab. Future research should examine the long-term residual effects of biochar across successive crop cycles, its performance across contrasting soil types and water regimes and conduct farm-level economic evaluations to support farmer adoption.

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Authors' contributions

ZTA conceived and conducted the research and performed the data analysis. SK supervised the research project. ZTA, SK and MA contributed to the review and editing of the manuscript, data analysis, original draft preparation, software support and

visualisation. All authors have read and approved the final manuscript.

Compliance with ethical standards

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly solely for language editing and grammar improvement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. FAO. The state of food and agriculture 2023: Climate-smart agriculture. Rome: Food and Agriculture Organization; 2023.
2. OECD. Agricultural outlook 2024–2033. Paris: Organisation for Economic Co-operation and Development; 2024.
3. Cong M, Hu Y, Sun X, Yan H, Yu G, Tang G, et al. Long-term effects of sugarcane straw biochar application on the growth and physiological characteristics of maize. *Front Plant Sci.* 2023;14:1172425. <https://doi.org/10.3389/fpls.2023.1172425>
4. Laghari M, Mirjat MS, Hu Z, Fazal S, Xiao B, Hu M, et al. Effects of sugarcane straw biochar application rate on sandy desert soil properties and sorghum growth. *Catena.* 2015;135:313–20. <https://doi.org/10.1016/j.catena.2015.08.013>
5. Peng J, Han X, Li N, Chen K, Yang J, Zhan X, et al. Combined application of sugarcane straw biochar with fertilizer promotes nitrogen uptake in

- maize by increasing nitrogen retention in soil. *Biochar*. 2021;3(3):367–79. <https://doi.org/10.1007/s42773-021-00090-6>
6. Gopinath KA, Visha Kumari V, Singh VK, Shanker AK, Reddy KS, Kundu S, et al. Combined application of nano-DAP and conventional fertilizers improved agronomic and economic performance of rainfed maize, nutrient and energy use efficiency. *Front Agron*. 2025;7:1723814. <https://doi.org/10.3389/fagro.2025.1723814>
 7. Jaffar MT, Chang W, Zhang J, Mukhtar A, Mushtaq Z, Ahmed M, et al. Sugarcane bagasse biochar boosts maize growth and yield in salt-affected soil by improving soil enzymatic activities. *J Environ Manage*. 2024;363:121418. <https://doi.org/10.1016/j.jenvman.2024.121418>
 8. India Meteorological Department, Meteorological Centre Chandigarh. Punjab monthly weather report for June 2025 (01.06.2025–30.06.2025). Chandigarh (India): India Meteorological Department; 2025.
 9. India Meteorological Department. Climate summary for the month of June 2025. Climate Research and Services (CRS). New Delhi (India): India Meteorological Department; 2025.
 10. Nasar J, Ahmad M, Gitari H, Tang L, Chen Y, Zhou XB. Maize/soybean intercropping increases nutrient uptake, crop yield and modifies soil physio-chemical characteristics and enzymatic activities in the subtropical humid region based in Southwest China. *BMC Plant Biol*. 2024;24(1):434. <https://doi.org/10.1186/s12870-024-05061-0>
 11. Sun C, Sun J, Gao J, Liu J, Yu X, Wang Z, et al. Comprehensive application of bio-char and nitrogen fertilizer in dry-land maize cultivation. *Sci Rep*. 2022;12(1):13478. <https://doi.org/10.1038/s41598-022-16971-0>
 12. Singh UK, Korav S, Kumar S, Sujatha HT. Influence of planting systems and nutrient management on maize growth, yield and light interception in a maize-soybean intercropping system. *Indian J Agric Res*. 2025;59(10):1584–9. <https://doi.org/10.18805/IJARE.A-6286>
 13. Gomez KA, Gomez AA. Statistical procedures for agricultural research. New York: John Wiley & Sons; 1984.
 14. Duncan DB. Multiple range and multiple F tests. *Biometrics*. 1955;11(1):1–42. <https://doi.org/10.2307/3001478>
 15. Reddy KS, Shivay YS, Kumar D, Parida BK, Bora R, Borate RB, et al. Nano DAP augments productivity, phosphorus use efficiency and profitability of spring wheat. *Sci Rep*. 2025;15(1):24771. <https://doi.org/10.1038/s41598-025-92364-3>
 16. Zhang L, Zhang M, Li Y, Li J, Jing Y, Xiang Y, et al. Linkage of crop productivity to soil nitrogen dynamics under sugarcane straw biochar addition: a meta-analysis across field studies. *Agronomy*. 2022;12(2):247. <https://doi.org/10.3390/agronomy12020247>
 17. Faloye OT, Alatisle MO, Ajayi AE, Ewulo BS. Effects of sugarcane straw biochar and inorganic fertiliser applications on growth, yield and water use efficiency of maize under deficit irrigation. *Agric Water Manage*. 2019;217:165–78. <https://doi.org/10.1016/j.agwat.2019.02.044>
 18. Hu W, Zhang Y, Rong X, Fei J, Peng J, Luo G. Coupling amendment of sugarcane straw biochar and organic fertilizers increases maize yield and phosphorus uptake by regulating soil phosphatase activity and phosphorus-acquiring microbiota. *Agric Ecosyst Environ*. 2023;355:108582. <https://doi.org/10.1016/j.agee.2023.108582>
 19. Ali I, He L, Ullah S, Quan Z, Wei S, Iqbal A, et al. Sugarcane straw biochar addition coupled with nitrogen fertilization impacts on soil quality, crop productivity and nitrogen uptake under double-cropping system. *Food Energy Secur*. 2020;9(3):e208. <https://doi.org/10.1002/fes3.208>
 20. Golla B, Dechassa N, Mohammed W, Gezahegn AM. Impact of sugarcane straw biochar and inorganic fertilizers rates on soil properties and yield components of maize at Bako Western Ethiopia. *J Agric Food Res*. 2026;26:102698. <https://doi.org/10.1016/j.jafr.2026.102698>
 21. Abdul-Aziz AL, Abukari IA, Galadima MM, Haruna A, Abubakari M, Abdulai R. Sugarcane straw biochar effects on soil properties and yield of maize in Northern region, Ghana. *Discover Agric*. 2025;3(1):103. <https://doi.org/10.1007/s44279-025-00271-y>
 22. Wei Z, Han X, Wang Y, Zhang L, Gong P, Shi Y. Effects of sugarcane straw biochar, dual inhibitor and straw return on maize yield, soil physicochemical properties and microbial system under fertilization conditions. *Front Microbiol*. 2025;16:1570237. <https://doi.org/10.3389/fmicb.2025.1570237>
 23. Wang L, Yu B, Ji J, Khan I, Li G, Rehman A, et al. Assessing the impact of sugarcane straw biochar and nitrogen application on yield, water -nitrogen use efficiency and quality of intercropped maize and soybean. *Front Plant Sci*. 2023;14:1171547. <https://doi.org/10.3389/fpls.2023.1171547>
 24. Naeem MB, Jahan S, Rashid A, Shah AA, Raja V, El-Sheikh MA. Improving maize yield and drought tolerance in field conditions through activated sugarcane straw biochar application. *Sci Rep*. 2024;14:25000. <https://doi.org/10.1038/s41598-024-76082-w>
 25. Ning C, Liu R, Kuang X, Chen H, Tian J, Cai K. Nitrogen fertilizer reduction combined with sugarcane straw biochar application maintain the yield and nitrogen supply of rice but improve the nitrogen use efficiency. *Agronomy*. 2022;12(12):3039. <https://doi.org/10.3390/agronomy12123039>

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