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Combined Application of Biochar and Nitrogenous Fertilizers Influences Growth and Productivity of Rainy and Spring Seasons Maize

Ruchi Goyal[1]* | **M.S. Kahlon[1]**

[1]Department of Soil Science, Punjab Agricultural University, Ludhiana

Corresponding Author:
E-mail: ruchigoyal068@gmail.com

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ABSTRACT

The use of biochar and other organic amendments not only reduces fertilizer dosage but also improves crop growth and water productivity. A field study was conducted in rainy or *kharif* season maize (2019) and spring maize (2020) with main-plots having BN_1 (biochar @ 7.5 t ha^{-1} + N @ 75 kg ha^{-1}), BN_2 (biochar @ 7.5 t ha^{-1} + N @ 150 kg ha^{-1}), FN_1 (farmyard manure @ 20 t ha^{-1} + N @ 75 kg ha^{-1}), FN_2 (farmyard manure @ 20 t ha^{-1} + N @ 150 kg ha^{-1}), N_1 (N @ 75 kg ha^{-1}) and N_2 (N @ 150 kg ha^{-1}) and sub-plots with two irrigations, viz., $I_{0.6}$ (IW/CPE: 0.6) and $I_{0.9}$ (IW/CPE: 0.9). Higher plant height (2.96 m), SPAD value (58.55), stover yield (23.89 t ha^{-1}), cob yield (8.14 t ha^{-1}) and grain yield (5.78 t ha^{-1}) were obtained under BN_2 treatment compared to other treatments. BN_2 increased grain yield by 22.7% and 28.5%, and water productivity by 21.6% and 27.6% in rainy season and spring season compared to N_2. The $I_{0.6}$ treatment resulted in higher water productivity by 5.5% compared to $I_{0.9}$ during the spring season, but grain yield was significantly higher under the $I_{0.9}$ treatment. Therefore, BN_2 with $I_{0.9}$ is a viable practice for achieving higher crop productivity.

1 | INTRODUCTION

In the Indo-Gangetic Plains (IGP), diversification from puddled transplanted rice to maize is increasingly promoted due to maize's lower water requirement, higher water-use efficiency (WUE), and adaptability to both rainy (kharif) and spring seasons. Compared to the rainy season, spring maize benefits from higher solar radiation and reduced disease pressure, and often exhibits superior yield stability and WUE due to controlled irrigation and reduced biotic stress. Primary challenges of crop production in the subtropical region encompass insufficient soil fertility and water scarcity. Addressing these concerns demands research aimed at refining soil's physical and chemical attributes while enhancing water retention and crop water-use efficiency (WUE). Among all approaches, one promising strategy is soil amendment with biochar (Katterer *et al.,* 2019).

Biochar, a carbon-rich by-product of the thermal decomposition of crop biomass, offers the potential to transform agricultural residues from environmental burdens into valuable resources. Biochar is considered more effective than farmyard manure (FYM) or other organic amendments due to its greater stability, porosity, and long residence time in soil. Unlike FYM and compost, which decompose rapidly under the hot semi-arid climate of the IGP, biochar persists for years, improving soil aggregation, increasing water-holding capacity, and reducing evaporative losses. Its superior surface area and porosity enable it to retain nutrients and water, fostering the growth of beneficial microorganisms (Warnock *et al.,* 2007) and thereby affecting porosity, water retention, and hydraulic conductivity, thereby influencing plant growth and yield (Ajayi *et al.,* 2016). Biochar can retain more irrigation water and reduce irrigation frequency, effectively optimizing the limited water available for crops. Farmyard manure (FYM), a traditional method, is commonly used by farmers in maize cultivation in the IGP, as FYM decomposes rapidly under the hot, semi-arid climate. FYM improves soil fertility, provides balanced nutrition for plants, and significantly enhances the soil's physical, chemical, and biological properties. Higher FYM levels correlate with increased root and shoot growth, plant height, and nutrient uptake in maize (Dass *et al.,* 2008; Bandyopadhyay *et al.,* 2010; Dass *et al.,* 2013; Masood *et al.,* 2014). Similarly, several studies indicate that adding organic material in the field significantly improves soil physical properties and water conservation (Manna *et al.*, 2016; Sahoo *et al.,* 2017). Another important agricultural input is irrigation, which helps achieve optimal productivity. Maize requires 600–700 mm of water for its optimum growth (Reddy, 2006). Water deficiency at any growth stage hampers maize growth, reducing leaf area and plant height due to impaired cell division and leaf expansion (Soler *et al.,* 2007).

Innovative strategies to enhance water and crop productivity of maize involve optimum irrigation (IW/CPE: 0.6 or 0.9; Agbna *et al.,* 2017) and fertilization. This approach sustains productivity through improving soil water extraction by plant roots. Integrated approaches combining biochar and fertilizers are gaining traction to address water and fertility issues (Uzoma *et al.,* 2011; Akhtar *et al.,* 2014). The study was conducted with the hypothesis that combined application of biochar or FYM with nitrogenous fertilizer under different irrigation treatments would enhance maize grain yield, crop and water productivity. The objective was to study the interactive effect of biochar, nitrogen, farmyard manure and irrigation on maize and water productivity, and to optimize the irrigation and nitrogen levels under biochar and farmyard manure application in maize.

2 | MATERIALS AND METHODS

2.1 | Geographical Location and Microclimate of the Experimental Site

The field experiment was conducted during the rainy (kharif) season of 2019 and the spring season of 2020 on sandy loam soil at the research farm of the Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, India. The soil of the experimental site was sandy loam, non-calcareous, with moderate organic carbon content and a neutral pH. Detailed soil characteristics for the experimental site are presented in (Table 1).

Regarding the region's agroclimatic conditions, Ludhiana experiences a sub-tropical, semi-arid climate with hot and dry summers from April to June, followed by a humid, sultry climate from July to September, and chilly winters from November to January. The meteorological data were collected from the Department of Agrometeorology observatory at Punjab Agricultural University, Ludhiana, and are provided in (Table 2).

2.2 | Experimental Treatment Details

The biochar used in the experiment was procured from the Department of Soil Science, Punjab Agricultural University, Ludhiana. The biochar was produced from rice residues via slow pyrolysis. The field experiment was laid out in a split-plot design with three replications; experimental details are given in Table 3. The treatments consisted of six different soil amendments, denoted as BN_1 (biochar @ 7.5 t ha^{-1} + N @ 75 kg ha^{-1}), BN_2 (biochar @ 7.5 t ha^{-1} + N @ 150 kg ha^{-1}), FN_1 (farmyard manure @ 20 t ha^{-1} + N @ 75 kg ha^{-1}), FN_2 (farmyard manure @ 20 t ha^{-1} + N @ 150 kg ha^{-1}), N_1 (N @ 75 kg ha^{-1}) and N_2 (N @ 150 kg ha^{-1}) in main-plots and two regimes of irrigation i.e. IW/CPE: 0.6 and IW/CPE: 0.9 as $I_{0.6}$ and $I_{0.9}$, respectively, in sub-plots.

It is important to acknowledge that the organic amendments used in this study contributed additional macro- and micronutrients beyond nitrogen. Rice residue-derived biochar applied at 7.5 t ha^{-1} typically contributes approximately 68 kg N ha^{-1}, 118 kg P_2O_5 ha^{-1}, and 233 kg K_2O ha^{-1}, though exact values depend on pyrolysis conditions and feedstock composition. Similarly, farmyard manure applied at 20 t ha^{-1} contributes substantial quantities of N, P, and K in addition to the inorganic nitrogen supplied by the treatment. Phosphorus was applied uniformly as

HIGHLIGHTS

- Biochar @ 7.5 t ha^{-1} combined with 150 kg N ha^{-1} (BN_2) increased maize grain yield by 22.7% and 28.5% in rainy and spring seasons, respectively, over nitrogen alone (N_2).
- BN_2 improved water productivity by 21.6% (rainy season) and 27.6% (spring season) relative to N_2, demonstrating superior resource-use efficiency.
- Where biochar is unavailable, farmyard manure @ 20 t ha^{-1} with 150 kg N ha^{-1} (FN_2) yields similar to BN_2, providing a cost-effective option for resource-limited farmers.
- The IW/CPE 0.9 irrigation regime maximized grain yield, while IW/CPE 0.6 increased water productivity by 5.5%; BN_2 with IW/CPE 0.9 is recommended for northwest India.

TABLE 1 Soil characteristics of experimental site

Depth (cm)	pH	EC (dS m^{-1})	OC (%)	Sand (%)	Silt (%)	Clay (%)	FC (%)	PWP (%)
0-15	7.4	0.21	0.52	67.6	18.2	14.1	23.8	13.7
15-30	7.3	0.20	0.45	66.8	17.3	16.0	24.2	12.1
30-60	7.2	0.17	0.26	62.3	19.4	18.2	24.1	11.9
60-90	7.6	0.18	0.16	58.9	20.1	20.9	25.4	12.8
90-120	7.7	0.16	0.12	58.6	20.6	20.7	25.0	14.5

TABLE 2 Climatic data of the crop growing periods

Month	Max. temp (°C)	Min. temp (°C)	Evaporation (mm)	Rainfall (mm)	Month	Max. temp (°C)	Min. temp (°C)	Evaporation (mm)	Rainfall (mm)
	Rainy Season					Spring Season			
June	40.4	25.8	291.4	29.9	Feb	21.5	8.5	57.8	15.0
July	34.0	26.7	174.1	218.4	Mar	24.5	12.9	79.4	69.0
August	33.8	26.1	131.4	331.4	Apr	32.8	17.7	138.3	13.2
September	33.1	25.5	101.1	264.8	May	36.9		213.0	49.6
October	30.6	18.4	76.7	0.0	June	37.6	26.5	220.4	9.6
Total	-	-	774.7	844.5	Total	-	-	708.9	156.4

single super phosphate, and potassium as muriate of potash, as basal doses across all treatments in spring maize. However, because P and K contributions from biochar and FYM were not separately quantified and deducted from basal fertilizer applications, the total P and K supply was not strictly balanced across amendment treatments. Readers should therefore interpret treatment comparisons with the awareness that biochar and FYM treatments received additional P and K relative to the N-only control treatments. This nutrient confounding is acknowledged as a limitation and is discussed further in Section 4. Both biochar and farmyard manure were reapplied to the soil during land preparation in both *kharif* maize and *spring* maize crops. This was done deliberately to evaluate the agronomic response to annual application of amendments rather than residual carry-over effects, and to assess whether the benefits observed in the first year were reproducible and potentially cumulative under repeated inputs.

2.3 | Details of Cultural Operations

2.3.1 | Field Preparation

A pre-sowing irrigation was applied to ensure optimal soil moisture for proper seed germination. After the harvesting of the previous crop toria, the field was prepared by ploughing twice with a disc harrow at optimum soil moisture conditions, followed by planking for kharif maize, and again after kharif maize toria was sown. The field was levelled to ensure proper irrigation and drainage. Farmyard manure and biochar were applied @ 20 tonnes per ha and @ 7.5 tonnes per ha, respectively, to the plots as shown in the layout before sowing.

2.3.2 | Sowing and Fertilizer Application

The sowing of the kharif maize and spring maize crop was done on 15th June 2019 and 4th February 2020 with a 20 kg ha^{-1} of seed rate; seed treatment was given with Bavistin @ 3 g kg^{-1} of seed. PMH10 variety was sown with the spacing of 60 cm between rows and 20 cm between plants. Phosphorus was applied as single super phosphate, potassium as muriate of potash, and zinc as $ZnSO_4$ in spring maize. The whole of the phosphorus, potassium, and zinc were applied as a basal dose before planting in the field, and nitrogen was applied in three splits at the recommended stages of the crop, i.e., at sowing, knee-high stage, and at pre-tasseling stage in the spring maize crop.

TABLE 3 Experimental details

Location	Soil Research Farms, Punjab Agricultural University, Ludhiana
Design	Split-Plot Design
Replications	Three
Treatments	Twelve
Gross Plot Size	4.30 m X 4.30 m
Net Plot Size	4 m X 4 m
Spacing	60 cm X 20 cm
Variety	PMH10

2.3.3 | Weeding and Irrigation

One spray of Atrataf 50 WP (atrazine) @ 800 g per acre in 200 litres of water was given up to 10 days after sowing, and then one hoeing was done at 30 days after sowing. Irrigation scheduling was made using IW/CPE (Irrigation water over cumulative open pan evaporation) method. Two irrigation regimes, i.e., IW/CPE = 0.6 and 0.9, were adopted for irrigation scheduling. The pan evaporation values were summed daily until they equaled the ratio of the amount of water applied as irrigation. Irrigation water was quantified using water meters installed in the field. Irrigation details are given in (Table 4).

2.4 | Crop Growth Measurements

Ten plants were randomly selected from each plot, and their height was measured from the ground surface to the top of the plant, including the flag leaf, at 80 days after sowing (DAS). Subsequently, the measurements were averaged for each individual plant. The SPAD value, which indicates chlorophyll content in the leaves, was determined using the Minolta SPAD 502 Chlorophyll Meter at 75 DAS. Stover and grain from a 9.6 square metre area in each plot were collected after harvesting, dried, and then weighed, and the weight was converted to metric tonnes per hectare.

2.5 | Statistical Analysis

To assess treatment effects, data collected across various parameters were subjected to analysis of variance (ANOVA) using a split-plot design in SAS software version 9.3 (SAS Institute Ltd, Cary, NC, USA). Treatment means were compared using the least significant difference (LSD) test at P = 0.05. F-values and associated P-values are reported alongside LSD values in the data tables. Mean separation letters (a, b, c…) are assigned such that means sharing the same letter are not significantly different at P = 0.05.

TABLE 4 Irrigation details according to the treatments during both seasons

	Rainy season $I_{0.6}$	Rainy season $I_{0.9}$	Spring season $I_{0.6}$	Spring season $I_{0.9}$
Number of irrigation per treatment	-	1	9	11
Water depth per irrigation event (mm)	0 mm	70 mm	70 mm	70 mm
Total irrigation water (mm)	-	70 mm	630 mm	770 mm
Rainfall during crop period (mm)	844.5 mm	844.5 mm	156.4 mm	156.4 mm
Rainfall + Irrigation (mm)	844.5 mm	914.5 mm	786.4 mm	926.4 mm

Water productivity (WP; kg ha^{-1} mm^{-1}) was calculated as grain yield (kg ha^{-1}) divided by total water input, where total water input = seasonal rainfall + total irrigation applied in each treatment (as shown in Table 4).

3 | RESULTS AND DISCUSSION

The maize crop responded positively to biochar application along with nitrogenous (N) fertilizer with respect to plant height and SPAD value (Table 5). There was no significant difference between biochar-amended soil and unamended soil on plant height and SPAD value in *kharif* maize 2019. However, in the spring maize season 2020, a notable and statistically significant difference was observed. Significant statistical differences were recorded among treatments on plant height taken at 80 DAS, with maximum plant height observed in BN_2 (2.74 m) followed by BN_1 (2.65 m), FN_2 (2.58 m), FN_1 (2.54 m), N_2 (2.44 m), and N_1 (2.43 m), respectively, during spring maize 2020. The increase in plant height with the application of biochar, along with a higher N dose, could be attributed to adequate nutrient supply; N had a positive effect on vigorous vegetative growth. Biochar application is associated with improved plant growth, consistent with reported mechanisms of enhanced nutrient retention and soil structure (Rahayu *et al.,* 2022). On the other hand, a significantly higher SPAD value was obtained with BN_2 than with other treatments. Even biochar with lower N (BN_1) showed 6.47% increase in SPAD value over farmyard manure with higher N (FN_2) in 2020. An increase in SPAD value might be due to the application of biochar along with a higher dose of nitrogen, which supplies essential nutrients to the crop, as nitrogen is considered an essential constituent of chlorophyll (Ghosh & Dass, 2019). Numerous research studies have shown that the use of biochar can substantially enhance soil nutrient levels, thereby influencing crop growth (Cong *et al.,* 2023).

Biochar and farmyard manure, along with nitrogen, also increased maize cob and grain yields over unamended plots across all irrigation regimes (Table 6). Cob yield significantly increased under BN_2 (8.14 and 8.88 t ha^{-1}) than N_2 (6.63 and 7.39 t ha^{-1}) in the rainy season and the spring season. The grain yield increased from 4.41 t ha^{-1} and 5.29 t ha^{-1} under N_1 to 5.78 t ha^{-1} and 6.95 t ha^{-1} in BN_2 during the rainy season and the spring season, respectively. With the increase in irrigation frequency, the grain yield of maize also increased from 4.94 t ha^{-1} in $I_{0.6}$ to 5.52 t ha^{-1} in $I_{0.9}$ during the rainy season, while the corresponding increase during the spring season was from 5.87 t ha^{-1} in $I_{0.6}$ to 6.56 t ha^{-1} in $I_{0.9}$. Significant interactive effects of different amendments with irrigation regimes were also observed for both years. The increase in maize yield was associated with the positive effects of biochar on various soil properties — including reported improvements in water retention and nutrient adsorption — and on microbial activity, resulting in the supply of additional nutrients for plant growth, as reported by several studies (Sun *et al.,* 2023). The use of biochar combined with nitrogen had a notable positive impact on maize growth, likely due to enhanced nutrient availability provided by the biochar (Abukari *et al.,* 2018). It should, however, be noted that the biochar and FYM treatments also supplied substantial additional P and K beyond the inorganic basal fertilizer applications common to all treatments. Consequently, the superior performance of BN_2 and FN_2 relative to N_2 may partly reflect the combined NPK effect of these amendments, particularly the substantial potassium contribution from biochar, rather than enhanced nitrogen management alone. Future studies should balance P and K inputs across treatment groups to isolate the specific contributions of nitrogen- and carbon-based fractions.

Water productivity (WP) of the crop as affected by different amendments and irrigation regimes is presented in Table 6. Highest water productivity was observed under BN_2 (6.52 and 8.10 kg ha^{-1} mm^{-1}), which was statistically at par with FN_2 (6.55 and 7.98 kg ha^{-1} mm^{-1}) but was significantly higher than N_2 (5.36 and 6.35 kg ha^{-1} mm^{-1}) and N_1 (4.99 and 6.2 kg ha^{-1} mm^{-1}) during both 2019 and 2020. Whether biochar was applied in conjunction with nitrogen or with farmyard manure and nitrogen, the crop's water productivity showed no statistically significant difference, but it was notably higher than with nitrogen alone. In essence, both biochar and farmyard manure had an equivalent positive impact on the crop's water productivity. Additionally, the choice of irrigation regime had a substantial influence on water productivity, with higher water productivity observed under $I_{0.6}$ (7.47 kg ha^{-1} mm^{-1}) in contrast to $I_{0.9}$ (7.08 kg ha^{-1} mm^{-1}) during 2020. Under mild water stress ($I_{0.6}$), the crop likely developed a deeper root system, drawing moisture from deeper soil layers as opposed to frequent irrigation ($I_{0.9}$), resulting in higher yields per unit of water and consequently elevated water productivity (Alsayim *et al.,* 2013).

The benefits of organic amendment application were markedly stronger in the spring season of 2020 than in the kharif season of 2019, with grain yield improvements over the N_2 control increasing from approximately 22.7% to 28.5% for BN_2, and water productivity gains rising from 21.6% to 27.6% across the same comparison. Several factors likely explain this intensification of response. First, the contrasting seasonal conditions between the two years — kharif 2019 received 844.5 mm of rainfall, which may have diluted the amendment effects through leaching and waterlogging, whereas spring 2020 received only 156.4 mm — meant that the water-retention benefits of biochar were far more agronomically relevant in the drier spring environment. Second, because biochar and FYM were reapplied in both years, the spring 2020 crop benefited from a cumulative increase in soil amendment load, potentially enhancing soil structural and nutrient-retention properties beyond what a single application could achieve. Third, the cooler, lower-humidity spring season environment reduces the rate of organic matter decomposition, allowing the amendments to contribute to nutrient supply over a longer period relative to the hot and humid kharif season. Taken together, these factors suggest that the agronomic value of biochar application is likely to be greatest in irrigated spring maize systems in the IGP, where seasonal aridity makes soil water retention a primary yield-limiting constraint.

TABLE 5 Effect of biochar and irrigation regimes on plant height, SPAD value, and stover yield of maize

Irrigation regime	Amendments													
	BN_1	BN_2	FN_1	FN_2	N_1	N_2	Mean	BN_1	BN_2	FN_1	FN_2	N_1	N_2	Mean
	Plant height (m)							Plant height (m)						
	Rainy season							Spring season						
$I_{0.6}$	2.8	3.0	2.9	3.0	2.8	2.9	2.9	2.6	2.7	2.5	2.6	2.4	2.5	2.6
$I_{0.9}$	3.0	2.8	2.7	2.8	2.8	2.8	2.8	2.6	2.7	2.5	2.6	2.4	2.4	2.6
Mean	2.9	2.9	2.8	2.9	2.8	2.8		2.6	2.7	2.5	2.6	2.4	2.4	
LSD	A=0.1; I=0.06; A X I= 0.146							A= 0.03; I= NS; A X I= NS						
	SPAD Value							SPAD Value						
	Rainy season							Spring season						
$I_{0.6}$	55.0	55.7	56.6	55.4	56.8	51.6	55.2	52.4	54.6	47.4	49.2	43.4	45.7	48.8
$I_{0.9}$	60.3	61.4	51.9	56.9	49.4	55.0	55.8	52.2	54.8	47.3	49.0	43.5	45.2	48.7
Mean	57.7	58.5	54.3	56.2	53.1	53.3		52.3	54.7	47.4	49.1	43.5	45.4	48.8
LSD	A= NS; I= NS; A X I= 4.20							A= 1.71; I= NS; A X I= NS						
	Stover yield (t ha^{-1})							Stover yield (t ha^{-1})						
	Rainy season							Spring season						
$I_{0.6}$	23.4	24.1	21.2	21.8	20.3	20.3	21.8	25.7	26.2	21.9	23.5	21.8	22.9	23.7
$I_{0.9}$	21.5	23.7	19.8	21.4	19.9	20.6	21.1	25.8	28.6	24.6	25.4	23.8	23.2	25.4
Mean	22.4	23.9	20.5	21.6	20.1	20.4		25.7	27.4	23.3	24.4	22.8	23.1	24.5
LSD	A= 0.7; I=0.7; A X I= 1.8							A= 0.8; I= 0.8; A X I= 1.8						

TABLE 6 Effect of biochar and irrigation regimes on cob yield, grain yield, and water productivity of maize

Irrigation regime	Amendments													
	BN_1	BN_2	FN_1	FN_2	N_1	N_2	Mean	BN_1	BN_2	FN_1	FN_2	N_1	N_2	Mean
	Cob yield (t ha^{-1}) Rainy season							Cob yield (t ha^{-1}) Spring season						
$I_{0.6}$	7.60	6.64	7.47	7.56	5.58	6.85	6.95	8.09	7.79	7.91	7.94	6.75	7.33	7.63
$I_{0.9}$	7.41	9.64	7.14	7.43	7.24	6.41	7.55	9.66	9.97	7.92	8.07	6.92	7.46	8.33
Mean	7.50	8.14	7.31	7.49	6.41	6.63		8.87	8.88	7.91	8.01	6.83	7.39	
LSD	A= 0.33; I= 0.20; A X I= 0.50							A= 0.49; I= 0.36; A X I= 0.88						
	Grain yield (t ha^{-1}) Rainy season							Grain yield (t ha^{-1}) Spring season						
$I_{0.6}$	5.39	4.72	5.37	5.58	3.77	4.83	4.94	6.23	6.31	6.19	5.96	5.19	5.37	5.87
$I_{0.9}$	5.62	6.83	5.08	5.95	5.05	4.59	5.52	6.88	7.59	6.28	7.78	5.39	5.45	6.56
Mean	5.51	5.78	5.22	5.77	4.41	4.71		6.55	6.95	6.23	6.87	5.29	5.41	
LSD	A= 0.36; I= 0.14; A X I= 0.34							A= 0.49; I= 0.41; A X I= 1.01						
	WP (kg ha^{-1} mm^{-1}) Rainy season							WP (kg ha^{-1} mm^{-1}) Spring season						
$I_{0.6}$	6.38	5.65	6.35	6.60	4.46	5.71	5.85	7.92	8.02	7.87	7.57	6.59	6.82	7.47
$I_{0.9}$	6.14	7.46	5.55	6.50	5.52	5.01	6.03	7.42	8.19	6.77	8.39	5.81	5.88	7.08
Mean	6.26	6.55	5.95	6.55	4.99	5.36		7.67	8.10	7.32	7.98	6.20	6.35	
LSD	A= 0.28; I= 0.15; A X I= NS							A= 0.82; I=0.35; A X I=NS						

4 | Limitations

Despite benefits of biochar on water efficiency and crop yield, several study limitations exist. Key soil properties like organic carbon, water holding capacity (WHC), and cation exchange capacity (CEC) were not directly measured; thus, yield explanations are inferred from literature, not confirmed in-situ. Treatments weren't balanced for phosphorus and potassium, as organic amendments added extra P and K beyond basal fertilizers, confounding results. Root measurements were missing, limiting claims about deep root growth and water extraction under deficit irrigation. Biochar properties such as surface area and porosity weren't characterized, affecting reproducibility. Being a single-location, two-season study in Ludhiana, Punjab, caution is needed when applying findings elsewhere; multi-location trials are advised. No economic analysis was performed, so the cost-benefit of biochar for smallholders remains unassessed.

5 | CONCLUSIONS

This study demonstrated that the combined application of biochar with nitrogen fertilizer, under an irrigation regime of IW/CPE 0.9, produced the highest maize grain yield and water productivity across both kharif and spring seasons. Results support three practical management scenarios depending on farmer objectives and resource availability:

1. **Maximum Productivity Goal:** BN_2 (biochar @ 7.5 t ha^{-1} + N @ 150 kg ha^{-1}) combined with $I_{0.9}$ (IW/CPE: 0.9) is the most effective practice for achieving the highest grain yield in northwest India. This treatment produced grain yields of 5.78 t ha^{-1} (rainy season) and 6.95 t ha^{-1} (spring season), representing 22.7% and 28.5% improvements over the N_2 control, respectively.
2. **Water-Limited Conditions:** Where irrigation water is scarce, BN_2 combined with $I_{0.6}$ (IW/CPE: 0.6) offers a viable alternative. While grain yield under $I_{0.6}$ was approximately 11% lower than under $I_{0.9}$ in spring season (6.31 vs. 7.59 t ha^{-1} for BN_2), water productivity was approximately 5.5% higher, making this combination suitable where maximizing output per unit of water is the priority.

3. **Resource-Constrained Farmers**: Where biochar is unavailable or economically prohibitive, FN_2 (farmyard manure @ 20 t ha^{-1} + N @ 150 kg ha^{-1}) combined with $I_{0.9}$ produced results comparable to $BN_2 + I_{0.9}$, particularly for grain yield and water productivity. This represents a practical, locally accessible alternative using on-farm organic resources.

It is important to note that the observed superiority of biochar-based treatments may partly reflect additional P and K contributions from the amendment rather than nitrogen and carbon effects alone. Economic analysis comparing amendment costs against yield benefits has not been conducted and is strongly recommended before blanket adoption recommendations are made, particularly for smallholder farming systems.

The findings also highlight the particular promise of biochar application in spring maize systems, where low seasonal rainfall makes soil water retention a primary yield-limiting factor. Future research should focus on long-term field experiments to evaluate the cumulative effects of biochar on soil hydraulic properties, carbon sequestration, and nutrient use efficiency in spring maize-based systems. Policy support for crop-residue-based biochar production, alongside incentives for water-saving technologies, can play a crucial role in making spring maize a climate-resilient and resource-efficient option in the Indo-Gangetic Plains.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY

Data will be made available on request.

AUTHOR'S CONTRIBUTION

Ruchi Goyal: writing original draft, data analysis; M.S. Kahlon: supervision and editing.

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