



RESEARCH ARTICLE

Optimising wheat productivity through graded nitrogen, phosphorus and potassium fertilisation and rice-straw biochar-farmyard manure integration in the rice-wheat system of Punjab

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Abstract

A field experiment was conducted during rabi 2024–25 at Lovely Professional University, Phagwara, Punjab, to evaluate graded nitrogen, phosphorus, potassium (NPK) fertiliser levels [100 % recommended dose of fertilisers (RDF) vs. 75 % nitrogen (N) with varying phosphorus–potassium (P–K) combinations] and organic amendments [control, 5 t ha⁻¹ rice-straw biochar, 7.5 t ha⁻¹ farmyard manure (FYM), 50:50 biochar: FYM] on wheat (*Triticum aestivum* L. cv. PBW 826) grown in nutrient-poor sandy loam [0.49 % soil organic carbon (SOC)] under rice–wheat rotation. Using a strip-plot design (3 replications) measurements included growth, physiological parameters [relative water content (RWC), membrane stability index (MSI), chlorophyll] and yield. 100 % RDF (M₁) significantly outperformed deficient treatments, recording 24–35 % greater plant height (PH), 38–64 % more tillers, 32–97 % higher RWC/MSI/chlorophyll and 47 % greater grain yield (GY) (56.00 q ha⁻¹) vs. M₅ (38.21 q ha⁻¹). Combined biochar: FYM (T₄) proved superior among amendments, enhancing growth (10–17 %), physiological parameters (14–25 %) and yield (14 % over control; 50.13 q ha⁻¹) through biochar's nutrient retention and FYM's labile N/microbial stimulation. Non-significant interactions indicated additive effects, with M₁+T₄ optimal. Biochar's porosity improved water retention/microbial habitats; full NPK sustained photosynthesis/remobilisation for grain filling. Potassium (K) omission caused severe penalties in vegetative/grain growth, underscoring the need for balanced nutrition. Results demonstrate that integrated 100 % RDF + 50:50 biochar: FYM optimises productivity (exceeding the Punjab average of ~45 q ha⁻¹), valorises rice residue (mitigating stubble burning) and builds soil health in Punjab's depleted loams-offering sustainable integrated nutrient management (INM) for rice–wheat systems.

Keywords: biochar; farmyard manure; integrated nutrient management; NPK fertilisation; wheat

Introduction

Wheat (*Triticum aestivum* L.) is the second most important staple food crop globally, feeding over 40 % of the world's population and contributing approximately 20 % of total dietary calories and protein (1). In India, wheat occupies a pivotal position in the national food security system, with nearly 31 million hectares under cultivation and an annual total of over 110 million tonnes, ranking second only to China in global wheat output (2). The Indo-Gangetic Plains particularly the northwestern states of Punjab, Haryana and western Uttar Pradesh, constitute the "bread basket" of India, contributing over 70 % of the country's wheat procurement for the public distribution system (3). Within this region, Punjab alone contributes approximately 40 % of the central pool of wheat, despite occupying only 1.5 % of the country's geographical area, underscoring the critical importance of sustaining and enhancing wheat productivity in this intensively cultivated zone (4).

The rice–wheat cropping system (RWCS) is the predominant agricultural production system in northwestern India, covering about 10.5 million hectares and providing livelihoods to millions of

farmers (5). This system has been instrumental in ensuring food security since the green revolution era, but is now facing serious challenges, including declining factor productivity, soil health degradation, groundwater depletion and environmental pollution (5). Continuous adoption of the rice–wheat rotation has spanned 5 decades. Over this period, imbalanced and excessive use of chemical fertilisers has led to multi-nutrient deficiencies, particularly of nitrogen (N), phosphorus (P) and potassium (K), as well as micronutrients such as zinc (Zn) and iron (Fe) (6). The sandy loam soils predominant in central Punjab are inherently low in organic carbon and have poor water and nutrient-holding capacity, making them particularly vulnerable to fertility depletion under intensive cultivation (7). The initial soil analysis at the present experimental site revealed an organic carbon content of only 0.49 %, available N of 176 kg ha⁻¹ and available K of 41 mg kg⁻¹, confirming the low-to-medium fertility status typical of this region (8).

N, P and K are the primary macronutrients governing wheat growth and productivity, collectively regulating chlorophyll synthesis, energy transfer, root development, stomatal function and

the translocation of assimilates from source to sink tissues (9–12). The recommended dose of fertilisers (RDF) for wheat in Punjab is 50:25:20 kg acre⁻¹ of N:P:K, based on extensive research conducted under diverse agro-climatic conditions. However, escalating fertiliser costs, imbalanced application practices and growing environmental concerns necessitate exploring strategies to optimise fertiliser use efficiency while maintaining or enhancing productivity.

The concept of integrated nutrient management (INM) has emerged as a sustainable approach to address the challenges of soil degradation and declining fertiliser efficiency (13). INM advocates the combined use of inorganic fertilisers and organic amendments to synchronise nutrient release with crop demand, improves physical and biological properties and enhance overall resource-use efficiency (14). Among organic amendments, farmyard manure (FYM) has long been used in Indian agriculture, valued for its ability to supply macro and micronutrients, improve soil structure, increase water-holding capacity and stimulate microbial activity (15). However, the limited availability of FYM due to competing uses and declining livestock populations per unit cultivated area has restricted its widespread application at recommended rates (16).

In recent years, biochar has gained considerable attention as a promising soil amendment with multiple agronomic and environmental benefits. Biochar is a carbon-rich material produced through pyrolysis of organic biomass under oxygen-limited conditions (17). When applied to soil, biochar can improve physical properties by reducing bulk density, increasing porosity and enhancing aggregate stability (18). Its high surface area and cation-exchange capacity facilitate nutrient retention, thereby reducing losses through leaching and volatilisation (18). Chemically, biochar can modify soil pH, particularly in acidic soils and directly contribute nutrients depending on the feedstock and pyrolysis conditions (19). The rice-straw biochar used in this study, characterised by high carbon content (64.6 %), alkaline pH (10.2) and presence of K (2.1 %) and silicon (7.4 %), offers potential benefits beyond those of traditional organic amendments (20).

The choice of rice straw as a biochar feedstock is particularly significant for Punjab, where rice cultivation generates approximately 20 million tonnes of straw annually (21). With mechanised harvesting practices leaving large quantities of straw in fields, farmers often resort to open-field burning as a quick and inexpensive disposal method, despite regulatory restrictions (22). Straw burning releases massive amounts of greenhouse gases, particulate matter and aerosols, causing severe environmental and health consequences, including the documented "Delhi Smog" episodes each winter (23). Converting this agricultural waste into biochar offers a mutually beneficial strategy: it provides a valuable soil amendment while mitigating air pollution and recycling nutrients back to the soil (21).

While several studies have individually examined the effects of biochar or FYM on crop productivity, information on their combined application with graded levels of inorganic fertilisers, particularly under the specific conditions of Punjab's rice–wheat system, remains limited (24). The interactive effects of biochar and FYM with varying nitrogen-phosphorus-potassium (NPK) combinations especially the response to K omission, which is increasingly observed in Punjab soils warrant detailed investigation (25). Furthermore, understanding the physiological basis of crop response, as reflected in parameters such as relative water content (RWC), membrane stability and chlorophyll content, can provide

mechanistic insights into how INM enhances stress tolerance and productivity (25).

This study aimed to assess the impact of varying levels of NPK fertiliser on the growth, physiological responses, yield characteristics and overall productivity of wheat (*Triticum aestivum* L. cv. PBW 826) cultivated in a rice-wheat rotation within the sandy loam soils of Punjab. Additionally, it evaluated the comparative effectiveness of rice-straw biochar (5 t ha⁻¹), FYM (7.5 t ha⁻¹) and their combined application at a 50:50 ratio as organic amendments integrated with inorganic fertilisers on wheat performance.

Materials and Methods

Experimental site and location

A field experiment was conducted during the rabi season of 2024–25 (November 2024–April 2025) at the Research Farm of Lovely Professional University, Phagwara, district Kapurthala, Punjab, India. The experimental site is geographically located at 31°14'43.8" N latitude and 75°41'44.1" E longitude at an altitude of 252 m above mean sea level. The total experimental area was 1200 m² and the field's cropping history confirmed a long-established rice–wheat rotation in the kharif and rabi seasons, providing a representative baseline for assessing the effects of integrated organic amendments.

Climate and weather conditions

The experimental site experiences a subtropical climate characteristic of the Trans-Gangetic Plains agro-climatic zone of northern India. Meteorological conditions during the rabi 2024–25 wheat season [standard meteorological week (SMW) 44–17; November 2024–April 2025] at the experimental site are presented in Fig. 1. Maximum temperatures ranged from 14.89 °C (SMW 2) to 37.44 °C (SMW 17), while minimum temperatures varied between 3.29 °C (SMW 50) and 19.57 °C (SMW 17), reflecting typical Punjab winter cooling followed by spring warming. Relative humidity was high during winter (morning RH 90–96 %, evening RH 47–78 %) but declined towards harvest (morning RH 81–88 %, evening RH 28–37 %). Rainfall was minimal (total 12.25 mm across 6 events), wind speeds averaged 2–15 km h⁻¹, evaporation ranged from 0.74 to 5.79 mm and sunshine hours ranged from 1.71 to 1.84 hr, with shorter days during peak winter.

Soil characteristics

Prior to the initiation of the experiment, composite surface soil samples (0–15 cm depth) were collected from the experimental field and analysed for physico-chemical properties using standard methods (Walkley–Black method for organic carbon and Kjeldahl digestion for available nitrogen). The soil was classified as sandy loam in texture (sand 74.9 %, silt 14.1 %, clay 11.0 %), with a pH of 7.4 and an electrical conductivity of 0.17 dS m⁻¹. Initial organic carbon content was 0.49 %, with available nitrogen, phosphorus and potassium at 176 kg ha⁻¹, 8.95 mg kg⁻¹ and 41 mg kg⁻¹, respectively, indicating a low-to-medium fertility status. The initial physico-chemical soil properties are presented in Table 1.

Experimental design and treatments

The experiment was laid out in a strip-plot design with 3 replications and 20 treatment combinations. The net plot size was 5 × 4 m = 20 m² and the total experimental area covered 1200 m², accommodating 60 plots. Main plots comprised 5 fertiliser nutrient levels (M₁–M₅) and sub-plots comprised 4 organic amendment treatments (T₁–T₄), as detailed in Tables 2 and 3.

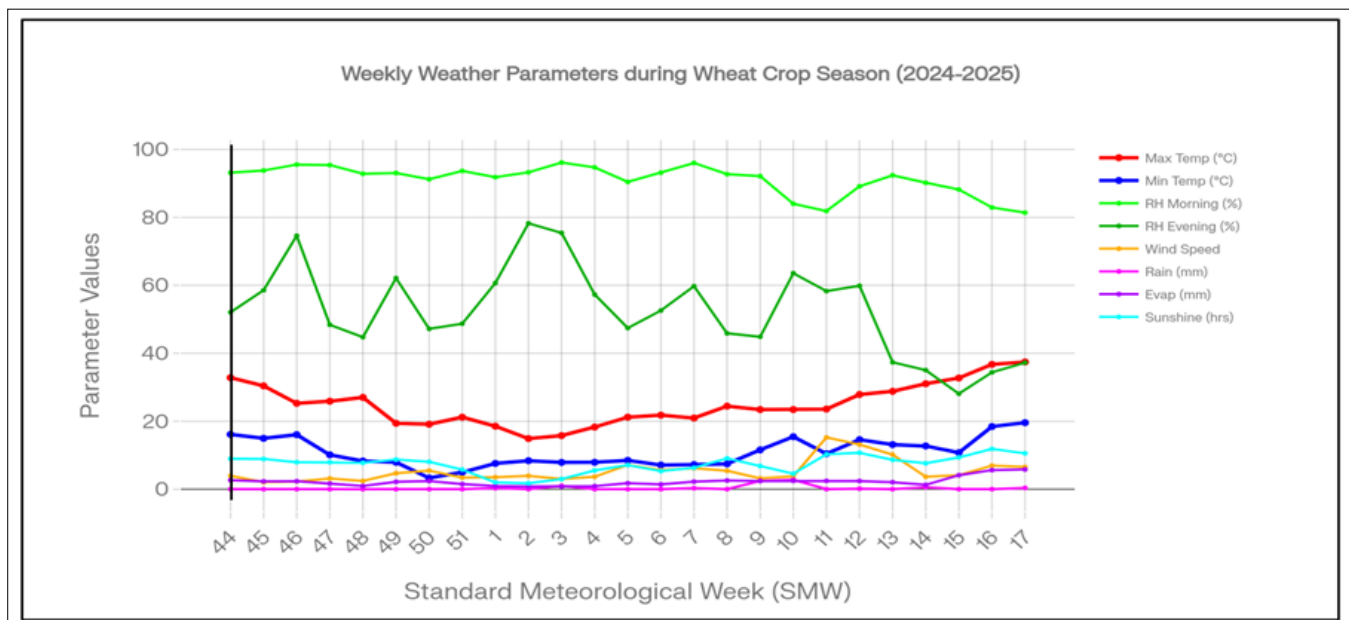


Fig. 1. Weekly meteorological data of the experimental site during November 2024–April 2025.

Table 1. Initial physico-chemical properties of experimental soil

Sl. No.	Soil characteristic	Value
1	Sand (%)	74.9
	Silt (%)	14.1
	Clay (%)	11.0
	Textural class	Sandy loam
2	pH	7.4
	EC (dS m ⁻¹)	0.17
	Organic carbon (%)	0.49
	Available N (kg ha ⁻¹)	176
	Available P (mg kg ⁻¹)	8.95
	Available K (mg kg ⁻¹)	41

Table 3. Treatment details of the research trial

Treatment	Details
Main plots	
M ₁	100 % NPK (RDF)
M ₂	75 % N + 100 % P + 100 % K
M ₃	75 % N + 100 % P + 0 % K
M ₄	75 % N + 50 % P + 100 % K
M ₅	75 % N + 50 % P + 0 % K
Sub-plots	
T ₁	Control (no amendment)
T ₂	5 t ha ⁻¹ Biochar (100 %)
T ₃	7.5 t ha ⁻¹ FYM (100 %)
T ₄	50 % Biochar + 50 % FYM

Preparation and characterisation of organic amendments

Biochar preparation

Rice-straw biochar was produced through open-fire carbonisation of sun-dried rice straw in a stainless-steel tub (height 48 cm, diameter 142 cm). The feedstock was ignited and pyrolysed at 400–600 °C under oxygen-limited conditions, with temperature monitored using a heat-sensing thermometer. Pyrolysis produced a carbon-rich char with a biochar yield of approximately 45–50 % on a dry-weight basis. After quenching with water, the biochar was air-dried and ground passed through a 2mm mesh sieve before field application.

Table 2. Experimental details of the research trial

Parameter	Details
Season	Rabi 2024 (November 2024–April 2025)
Crop and variety	Wheat (<i>Triticum aestivum</i> L.) PBW 826
Design of experiment	Strip-plot design
Number of treatments	20
Number of replications	3
Total number of plots	60
Net plot size	5 × 4 m = 20 m ²
Total experimental area	1200 m ²
Spacing	22.5 cm (row-to-row)
Fertiliser dose (N:P:K)	50:25:20 kg acre ⁻¹

Biochar characterisation

Biochar samples were characterised using field emission scanning electron microscopy (FESEM) (FESEM; JSM-7610F PLUS, Oxford Instruments, Japan) at an operating voltage of 15–25 kV after gold coating via an ion coater (D II-29030SCTR, Japan) to enhance conductivity. Concurrently, energy dispersive x-ray spectroscopy (EDS; OXFORD X-Max N, Japan) was performed to determine the elemental composition of the biochar. Key properties of the rice-straw biochar used are presented in Table 4.

Crop management and nutrient applications

Certified seeds of wheat cultivar PBW 826 (*Triticum aestivum* L.; timely-sown, high-yielding, *rabi* season) were procured from Punjab Agricultural University (PAU), Ludhiana and treated with carbendazim at 2 g kg⁻¹ seed before sowing as a prophylactic fungicidal measure. Seeds were drill-sown at a depth of 3–5 cm with 22.5 cm row-to-row spacing using a manual seed drill in a well-prepared, friable seedbed obtained after deep plowing (15–20 cm), one harrowing and planking. Bunds were constructed around each subplot to prevent runoff of nutrients and water between plots.

Table 4. Characteristics of rice-straw biochar used in the experiment

Characteristic	Rice-straw biochar
pH	10.2
Carbon	64.6 %
Oxygen	22.9 %
Potassium	2.1 %
Silicon	7.4 %
Magnesium	0.30 %

Nutrients were applied through urea, single superphosphate (SSP) and muriate of potash (MOP) at a recommended dose of 50:25:20 kg acre⁻¹ N:P:K as per main-plot treatment combinations. Full P and K along with 50 % of the N dose were incorporated as basal at sowing; the remaining 50 % N was top-dressed in two equal splits—the first at the crown root initiation (CRI) stage [~20–25 days after sowing = (DAS)] and the second at the late tillering/first-node stage (~40–45 DAS), coinciding with scheduled irrigations for efficient nutrient uptake. Biochar and farmyard manure (FYM) as sub-plot amendments (T₂, T₃, T₄) were incorporated into the soil at the time of final field preparation before sowing.

Irrigation was scheduled at critical crop growth stages: CRI, late tillering, jointing, booting, heading/flowering and grain-filling (milk dough) stages. Soil moisture status was assessed gravimetrically to guide irrigation scheduling (at 30–40 % depletion of field capacity), while avoiding waterlogging through proper bund management. Weed management was achieved through pre-emergence application of pendimethalin (1 kg a.i. ha⁻¹) at 1–2 DAS, followed by one hand weeding at 35 DAS. Standard plant protection measures, including need-based application of emamectin benzoate 5 % soluble granules (SG) for insect pest control, were carried out in accordance with integrated pest management (IPM) protocols and PAU recommendations. Harvesting was performed manually in the last week of April 2025, when the crop attained complete golden-brown coloration, indicating physiological maturity, with subsequent threshing done plot-wise.

Observations recorded

Growth parameters

Growth parameters were recorded at 30, 60, 90 and 120 DAS from 10 randomly tagged plants per plot. Plant height (cm) was measured using a graduated tape from the base to the tip of the tallest tiller. The number of tillers (m⁻²) was counted from a 1 m² area at each sampling interval. Leaf area (cm²) was measured at 30, 60 and 90 DAS using an automatic leaf area meter, and the leaf area index (LAI) was calculated by the following equation (26):

$$\text{LAI} = \text{Leaf area (m}^2\text{)} / \text{Ground area (m}^2\text{)} \quad \text{Eqn. 1}$$

Physiological parameters

Total chlorophyll (TC) content (mg g⁻¹ FW) was extracted from 100 mg of fresh leaf tissue using 20 mL of 80 % acetone and centrifuged at 5000 rpm for 10 min. Absorbance of the supernatant was recorded at 645 nm and 663 nm using a UV-Vis spectrophotometer and TC content was calculated as per standardised protocol (27), expressed as mg g⁻¹ fresh weight.

Relative water content (%) was determined from flag leaves. Fresh weight (FW) was recorded immediately after harvest. Leaf discs (2 cm) were floated on distilled water for 4 hr to obtain turgid weight (TW), then oven-dried at 60 °C for 24 hr to obtain dry weight (DW). Relative water content was calculated using the standard equation (28).

$$\text{RWC (\%)} = [(\text{FW} - \text{DW}) / (\text{TW} - \text{DW})] \times 100 \quad \text{Eqn. 2}$$

Membrane stability index (MSI, %) was measured using fresh leaf segments (200 mg) immersed in 10 mL of double-distilled water in 2 sets. Set-1 was heated at 40 °C for 30 min (C1) and Set-2 at 100 °C for 10 min (C2) in a water bath and electrical conductivity was measured in both sets. MSI was calculated by the standard equation (29).

$$\text{MSI (\%)} = 100 [1 - (\text{C1}/\text{C2})] \quad \text{Eqn. 3}$$

Yield and yield attributes

At physiological maturity, the following yield attributes were recorded from 10 randomly selected plants per plot: effective tillers (m⁻²), spike length (cm), grains per spikelet (GPS), test weight (TW) (g), grain yield (GY) (q ha⁻¹) and straw yield (SY) (q ha⁻¹). Grain from each net plot was weighed after threshing and air-drying and converted to q ha⁻¹. Straw yield was calculated by subtracting GY from biological yield (total above-ground biomass).

Statistical analysis

All recorded data were tabulated by treatment across 3 replications and subjected to analysis of variance (ANOVA) in RStudio. Standard error of the mean (SE(m) ±) and critical difference (CD) at the 5 % probability level were calculated using KAU GRAPES statistical software (30). Treatment means differing by more than the CD value at $p \leq 0.05$ were considered significantly different.

Results

Plant height

Plant height differed significantly among nutrient management treatments across all growth stages (Table 5), except at 30 DAS. At 90 DAS, plants under 100 % RDF (M₁) attained the maximum height (64.04 cm), which was statistically equivalent to M₂ (59.71 cm), while the lowest was recorded under M₅ (51.02 cm). At harvest, M₁ also maintained superiority (85.61 cm), followed by M₂ (76.03 cm), whereas the least height (63.48 cm) was observed in M₅. The increase in PH under 100 % RDF (M₁) over M₅ was 24–35 % across stages. No significant variation was noted on 30 DAS.

Among organic amendment treatments, PH differed significantly at all stages except 30 DAS. At harvest, T₄ (50 % biochar + 50 % FYM) recorded the maximum PH (75.56 cm), closely followed by T₂ and T₃, whereas T₁ (control) recorded the minimum (68.75 cm). The increase in PH under T₄ compared to the control ranged from 6 % to 10 % across stages. The interaction effects of nutrient management and organic amendments on PH were non-significant across all growth stages.

Number of tillers

The number of tillers was significantly influenced by nutrient management treatments at all crop growth stages (Table 6). At 30 and 60 DAS, application of 100 % NPK (M₁) recorded the highest tiller number (204.22 tillers m⁻²), which was statistically equivalent to M₂ (192.39 tillers m⁻²), while the lowest values were noted under M₅ (125.01 tillers m⁻²). At 90 DAS and harvest, M₁ also maintained superiority (409.19 and 409.91 tillers m⁻², respectively), followed by M₂, whereas M₅ produced the minimum (253.65 and 254.34 tillers m⁻²). The increase in tiller count under M₁ relative to M₅ ranged from 38 % to 64 % across stages.

Among sub-plot treatments, T₄ (50 % biochar + 50 % FYM) produced the maximum number of tillers at all stages (352.12 and 352.82 tillers m⁻² at 90 DAS and harvest, respectively), which was statistically equivalent to T₂ and T₃, while T₁ (control) recorded the minimum (302.02 and 302.69 tillers m⁻²). The increase in tiller number under T₄ relative to T₁ ranged from 10 % to 17 % during the crop growth period. The interaction between main-plot and sub-plot factors on the number of tillers was non-significant at all stages; therefore, results have been interpreted based on main effects only.

Table 5. Effect of nutrient levels and organic amendments on plant height (cm) of wheat (*Triticum aestivum* L.) at different growth stages during rabi 2024–25

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Main plot				
M ₁	25.64	47.29	64.04	85.61
M ₂	25.02	43.63	59.71	76.03
M ₃	26.51	39.55	53.58	67.29
M ₄	26.01	40.60	55.12	69.14
M ₅	25.76	37.58	51.02	63.48
SE(m) ±	1.60	0.09	0.51	0.21
CD at 5 %	NS	0.30	1.67	0.69
Sub-plot				
T ₁	24.72	40.10	54.83	68.75
T ₂	26.61	41.88	56.82	73.27
T ₃	26.01	41.74	56.29	71.65
T ₄	25.81	43.19	58.83	75.56
SE(m) ±	1.20	0.24	0.39	0.18
CD at 5 %	NS	0.83	1.36	0.61
Interaction: main plot × sub-plot				
SE(m) ±	2.79	0.47	0.87	0.45
CD at 5 %	NS	NS	NS	NS

Table 6. Effect of nutrient levels and organic amendments on the number of tillers (m⁻²) of wheat (*Triticum aestivum* L.) at different growth stages during rabi 2024–25

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Main plot				
M ₁	204.22	204.22	409.19	409.91
M ₂	192.39	192.39	376.39	377.08
M ₃	128.52	128.52	282.87	283.52
M ₄	154.77	154.77	314.18	314.83
M ₅	125.01	125.01	253.65	254.34
SE(m) ±	0.46	0.46	2.25	2.23
CD at 5 %	1.50	1.50	7.32	7.26
Sub-plot				
T ₁	152.18	152.18	302.02	302.69
T ₂	165.37	165.37	332.25	332.92
T ₃	155.19	155.19	322.63	323.31
T ₄	171.18	171.18	352.12	352.82
SE(m) ±	0.25	0.25	2.79	2.79
CD at 5 %	0.85	0.85	9.67	9.65
Interaction: Main plot × Sub-plot				
SE(m) ±	0.92	0.92	4.82	4.82
CD at 5 %	NS	NS	NS	NS

Leaf area

Leaf area was significantly affected by nutrient management treatments at all crop growth stages (Table 7). The 100 % NPK treatment (M₁) consistently recorded the highest leaf area at all stages (5.65, 12.81, 15.81 and 13.81 cm² at 30, 60, 90 DAS and harvest, respectively), while M₅ registered the lowest values (4.63, 9.72, 12.72 and 10.72 cm²). The increase in leaf area under M₁ over M₅ ranged from 22–30 % across growth stages. Among sub-plot treatments, T₄ recorded the highest leaf area at all stages (5.40, 11.75, 14.75 and 12.75 cm²), which was statistically equivalent to T₂ and T₃, whereas T₁ exhibited the minimum (4.90, 10.43, 13.43 and 11.43 cm²). The magnitude of the increase under T₄ compared to T₁ ranged from 10 % to 13 %. The interaction effect between main-plot and sub-plot treatments on leaf area was non-significant across all stages; hence, only the main effects are discussed.

Relative water content

Relative water content (RWC) of leaves was significantly influenced by nutrient management at all crop growth stages (Table 8). The 100 % NPK treatment (M₁) recorded the highest RWC across all stages (87.60, 79.02, 82.22 and 80.02 % at 30, 60, 90 DAS and harvest, respectively), while M₅ remained the lowest (59.89, 46.77, 51.97 and

47.77 %). The increase in RWC under M₁ over M₅ ranged from 32–40 % across growth stages. Among sub-plot treatments, T₄ consistently recorded the maximum RWC (77.28, 66.10, 70.10 and 67.10 % at 30, 60, 90 DAS and harvest, respectively), while T₁ registered the minimum values (67.12, 55.75, 59.95 and 56.75 %). The improvement in RWC under T₄ compared to T₁ ranged from 14 % to 17 %. The interaction effect between the main-plot and sub-plot factors on RWC was non-significant at all stages; therefore, the results have been interpreted based on the main effects only.

Membrane stability index

Membrane stability index of wheat leaves was significantly influenced by nutrient management at all crop growth stages (Table 9). The M₁ treatment consistently recorded the highest MSI across all stages (36.17, 57.36, 66.86 and 47.86 % at 30, 60, 90 DAS and harvest, respectively), while M₅ remained the lowest (20.64, 30.60, 33.97 and 28.81 %). The increase in MSI under M₁ compared to M₅ ranged from 39 % to 97 % across growth stages. Among sub-plot treatments, T₄ resulted in maximum MSI at all stages (31.00, 46.16, 53.36 and 38.88 %), while T₁ exhibited the minimum (26.28, 38.49, 45.73 and 32.97 %). The improvement in MSI from T₁ to T₄ ranged from 15–25 %. The interaction effect between main-plot and

Table 7. Effect of nutrient levels and organic amendments on leaf area (cm² plant⁻¹) of wheat (*Triticum aestivum* L.) at different growth stages during rabi 2024–25

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Main plot				
M ₁	5.65	12.81	15.81	13.81
M ₂	5.45	11.75	14.75	12.75
M ₃	5.05	10.73	13.73	11.73
M ₄	5.20	11.16	14.16	12.16
M ₅	4.63	9.72	12.72	10.72
SE(m) ±	0.10	0.25	0.24	0.26
CD at 5 %	0.32	0.81	0.80	0.86
Sub-plot				
T ₁	4.90	10.43	13.43	11.43
T ₂	5.29	11.44	14.44	12.44
T ₃	5.20	11.32	14.32	12.32
T ₄	5.40	11.75	14.75	12.75
SE(m) ±	0.09	0.21	0.18	0.21
CD at 5 %	0.31	0.73	0.62	0.73
Interaction: main plot × sub-plot				
SE(m) ±	0.20	0.44	0.46	0.48
CD at 5 %	NS	NS	NS	NS

Table 8. Effect of nutrient levels and organic amendments on relative water content (RWC, %) of wheat (*Triticum aestivum* L.) leaves at different growth stages during rabi 2024–25

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Main plot				
M ₁	87.60	79.02	82.22	80.02
M ₂	76.15	67.06	70.76	68.06
M ₃	68.77	55.49	59.69	56.49
M ₄	70.18	58.04	62.24	59.04
M ₅	59.89	46.77	51.97	47.77
SE(m) ±	0.88	3.92	4.09	3.95
CD at 5 %	2.86	12.78	13.32	12.87
Sub-plot				
T ₁	67.12	55.75	59.95	56.75
T ₂	73.76	61.86	65.86	62.86
T ₃	71.90	61.39	65.59	62.39
T ₄	77.28	66.10	70.10	67.10
SE(m) ±	0.52	3.74	3.57	3.54
CD at 5 %	1.78	NS	NS	NS
Interaction: main plot × sub-plot				
SE(m) ±	1.46	8.04	8.14	8.17
CD at 5 %	NS	NS	NS	NS

Table 9. Effect of nutrient levels and organic amendments on membrane stability index (MSI, %) of wheat (*Triticum aestivum* L.) leaves at different growth stages during rabi 2024–25

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Main plot				
M ₁	36.17	57.36	66.86	47.86
M ₂	32.14	47.28	55.78	38.78
M ₃	27.48	38.04	45.54	31.00
M ₄	29.29	39.14	45.13	33.01
M ₅	20.64	30.60	33.97	28.81
SE(m) ±	0.93	0.53	1.32	0.89
CD at 5 %	3.02	1.74	4.30	2.91
Sub-plot				
T ₁	26.28	38.49	45.73	32.97
T ₂	30.40	43.87	51.07	36.71
T ₃	28.90	41.40	47.67	35.00
T ₄	31.00	46.16	53.36	38.88
SE(m) ±	1.01	0.75	1.22	0.57
CD at 5 %	NS	2.58	4.22	1.97
Interaction: main plot × sub-plot				
SE(m) ±	2.10	1.69	2.59	1.54
CD at 5 %	NS	NS	NS	NS

sub-plot treatments on MSI was non-significant at all stages; hence, the results have been interpreted based on main effects only.

Total chlorophyll

Total chlorophyll content of wheat leaves was significantly influenced by nutrient management treatments at all crop growth stages (Table 10). Application of 100 % NPK (M_1) consistently recorded the maximum TC across all stages (3.72, 3.66, 3.76 and 1.96 mg g⁻¹ at 30, 60, 90 DAS and harvest, respectively), while M_5 produced the minimum (2.20, 3.19, 3.32 and 1.56 mg g⁻¹). The increase in TC under M_1 relative to M_5 ranged from 14 % to 69 % across growth stages. Among sub-plot treatments, T_4 recorded the highest TC at all stages (3.16, 3.54, 3.64 and 1.84 mg g⁻¹), while T_1 exhibited the lowest values (2.61, 3.34, 3.46 and 1.69 mg g⁻¹). The improvement in TC from T_1 to T_4 ranged from 9–21 %. The interaction between the main-plot and subplot factors for TC was non-significant at all stages; hence, the interpretation of the results was based solely on the main effects.

Table 10. Effect of nutrient levels and organic amendments on total chlorophyll content (mg g⁻¹ fresh weight) of wheat (*Triticum aestivum* L.) leaves at different growth stages during rabi 2024–25

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Main plot				
M_1	3.72	3.66	3.76	1.96
M_2	3.13	3.58	3.68	1.88
M_3	2.60	3.41	3.51	1.71
M_4	2.72	3.46	3.56	1.76
M_5	2.20	3.19	3.32	1.56
SE(m) ±	0.18	0.05	0.03	0.02
CD at 5 %	0.58	0.15	0.11	0.06
Sub-plot				
T_1	2.61	3.34	3.46	1.69
T_2	2.92	3.50	3.60	1.80
T_3	2.80	3.47	3.57	1.77
T_4	3.16	3.54	3.64	1.84
SE(m) ±	0.21	0.04	0.03	0.02
CD at 5 %	NS	NS	0.10	0.06
Interaction: main plot × sub-plot				
SE(m) ±	0.48	0.09	0.06	0.03
CD at 5 %	NS	NS	NS	NS

Table 11. Effect of nutrient levels and organic amendments on yield attributes and yields of wheat (*Triticum aestivum* L.) during rabi 2024–25

Treatment	Effective tillers (m ⁻²)	Spike length (cm)	Grains per spikelet	Test weight (g)	Grain yield (q ha ⁻¹)	Straw yield (q ha ⁻¹)
Main plot						
M^1	307.33	9.54	41.86	43.40	56.00	78.40
M^2	270.24	8.53	34.77	36.31	51.50	72.10
M^3	180.98	7.04	29.92	31.46	44.75	62.65
M^4	213.23	7.55	31.34	32.89	47.04	65.86
M^5	143.87	6.06	26.38	27.93	38.21	53.49
SE(m) ±	6.83	0.70	1.23	1.23	0.91	1.27
CD at 5 %	22.27	NS	4.00	4.00	2.97	4.15
Sub-plot						
T^1	196.80	7.43	29.50	31.05	43.93	61.51
T^2	228.45	8.05	33.77	35.31	48.47	67.85
T^3	218.90	7.45	32.55	34.09	47.47	66.45
T^4	248.36	8.04	35.60	37.15	50.13	70.19
SE(m) ±	9.63	0.52	0.67	0.67	0.76	1.07
CD at 5 %	33.33	NS	2.32	2.32	2.64	3.70
Interaction: main plot × sub-plot						
SE(m) ±	14.98	1.14	1.95	1.95	1.76	2.46
CD at 5 %	NS	NS	NS	NS	NS	NS

Yield and yield attributes

Application of 100% NPK (M_1) significantly improved wheat yield-attributing characters and yield compared with the other nutrient levels (Table 11). Effective tillers m⁻² was maximum under M_1 (307.33 m⁻²), statistically superior to all other main-plot treatments, while the minimum was recorded with M_5 (143.87 m⁻²) an increase of about 114 % under M_1 over M_5 . Spike length was not significantly different among main-plot treatments. The maximum GPS (41.86) and the highest TW (43.40 g) were obtained under M_1 , representing improvements of about 59 % and 55 % over M_5 . Consequently, M_1 produced the highest GY (56.00 q ha⁻¹) and SY (78.40 q ha⁻¹), corresponding to a 47 % advantage in GY over M_5 (38.21 q ha⁻¹).

Among organic amendment treatments, T_4 (50% biochar + 50 % FYM) proved most effective in improving yield attributes and yield. T_4 registered the maximum effective tillers (248.36 m⁻²), GPS (35.60), and TW (37.15 g), which were significantly superior to T_1 (196.80 m⁻²; 29.50 GPS; 31.05 g), reflecting improvements of 26 %, 21 %, and 20 %, respectively. This translated into maximum GY (50.13 q ha⁻¹) and SY (70.19 q ha⁻¹) under T_4 , representing 14 % gains

in grain and SY over the control. Grain yield and SY were found to be non-significant for the interaction between main-plot and sub-plot treatments; therefore, the results have been interpreted based on main effects only.

Discussion

The integrated application of inorganic fertilisers and organic amendments significantly influenced the growth, physiological parameters, yield attributes and productivity of wheat (*Triticum aestivum* L.) under subtropical conditions in Punjab. The findings demonstrate that combining optimal fertiliser levels with organic amendments creates synergistic effects that enhance crop performance through multiple mechanisms, including improved nutrient availability, enhanced soil physical properties and modulated plant physiological responses.

The superior growth parameters observed under 100 % NPK (M_1) and combined biochar + FYM application (T_4) can be attributed to enhanced nutrient availability throughout the crop growth cycle. Nitrogen, as an essential component of chlorophyll, proteins and nucleic acids, promotes vegetative growth through increased cell division and elongation (31). The full recommended NPK dose in M_1 ensured an adequate N supply during critical growth phases, explaining the 24–35 % increase in PH under M_1 compared to M_5 across growth stages. Similarly, the improved tillering capacity (38–64 % increase under M_1 over M_5) reflects the critical role of N in promoting tiller bud initiation and survival, corroborating findings of a previous study which reported that adequate N nutrition during early growth stages determines potential tiller numbers in wheat (32).

The organic amendments, particularly the combined application of biochar and FYM (T_4), enhanced growth parameters by improving the soil microenvironment. Biochar's high porosity and surface area (as evident from FESEM characterisation) increases soil water-holding capacity and provide refuge for beneficial microorganisms, while its alkaline pH (10.2) can ameliorate soil acidity and improve nutrient availability (33). Farmyard Manure complements this by supplying readily mineralisable organic N and stimulating microbial activity. The 10–17 % increase in tiller number under T_4 relative to control demonstrates this synergistic effect, consistent with observations of another study which reported that combined organic amendments improve soil aggregation and nutrient retention more effectively than sole applications (34). Although the interaction between nutrient levels and amendments was non-significant, the additive benefits suggest that organic amendments can partially offset reduced fertiliser inputs, as seen in M_2 treatments, where 75 % N combined with amendments maintained statistically comparable growth to full RDF.

The physiological parameters, including RWC, MSI and TC content, provide mechanistic insights into how nutrient management enhanced crop performance. The 32–40 % improvement in RWC under M_1 compared to M_5 reflects improved water uptake and retention capacity, likely mediated by enhanced root development and osmotic adjustment (35). Adequate K nutrition in M_1 regulates stomatal conductance and maintains cell turgor by accumulating solutes like proline and sugars (36). This explains why treatments with K omission (M_3 and M_5) showed consistently lower RWC values. The MSI, which increased by 39–97% under M_1 relative to M_5 , indicates reduced oxidative damage

to cell membranes (37). Potassium deficiency is known to increase membrane permeability by impairing the synthesis of membrane lipids and proteins, while adequate N and P support membrane integrity through phospholipid synthesis (38). The organic amendments further enhanced membrane stability (15–25 % increase under T_4 over control) by reducing stress-induced reactive oxygen species, possibly through improved silicon nutrition from biochar (7.4 % Si content), which strengthens cell walls (39).

Total chlorophyll content followed similar trends, with M_1 showing 14–69 % higher values than M_5 across growth stages. Chlorophyll synthesis requires adequate N as a structural component of the porphyrin ring (40). The gradual decline in chlorophyll content at harvest across all treatments reflects natural senescence and N remobilisation to developing grains (40). The organic amendments, particularly T_4 , maintained higher chlorophyll content during grain filling (9–21 % increase over the control), potentially extending the photosynthetically active period and contributing to higher GY. This aligns with findings of another study which reported that combined organic-inorganic fertilisation delays leaf senescence by maintaining better N status during reproductive stages (41).

The yield attributes and final productivity represent the culmination of improved growth and physiological processes. The 55–59 % improvements in GPS and TW under M_1 reflect improved pollination, fertilisation and grain filling, processes that are highly dependent on current photosynthesis and remobilised assimilates (43). The resulting GY (56.00 q ha⁻¹ under M_1) exceeds the Punjab state average (approximately 45 q ha⁻¹), indicating that the combination of improved variety (PBW 826) and optimal management achieved high productivity. The 47 % yield reduction under M_6 highlights the severe consequences of multi-nutrient deficiency, particularly K omission, which impaired both vegetative growth and grain development (44).

The organic amendments contributed significantly to yield improvement, with T_4 increasing GY by 14 % over the control (43.93 to 50.13 q ha⁻¹). This response can be attributed to multiple mechanisms: biochar's direct nutrient contribution (2.1 % K, 0.3 % Mg), improved nutrient use efficiency through reduced leaching, enhanced root proliferation in amended soil zones and sustained nutrient release from FYM during reproductive stages (45). Similar synergistic effects were reported in another study which observed that combined biochar-compost applications improved maize yields more than either amendment alone due to enhanced cation exchange capacity or microbial activity (46).

The non-significant interactions between fertiliser levels and organic amendments for all parameters indicate that these factors act additively rather than synergistically under the conditions of this study. This has important practical implications: farmers can expect consistent benefits from organic amendments regardless of their fertiliser management level. From a soil health perspective, the incorporation of biochar and FYM, even at moderate rates (5–7.5 t ha⁻¹), likely improved soil organic carbon content beyond the initial 0.49 %, contributing to long-term sustainability. Biochar's stability (64.6 % carbon content) ensures a prolonged soil residence time, while FYM provides labile carbon to support microbial activity (47). Future research should focus on the long-term effects of repeated applications of organic amendments on soil carbon sequestration, nutrient cycling and crop productivity under varying climatic conditions.

Conclusion

The field experiment carried out in rabi 2024–25 at Lovely Professional University, Phagwara, demonstrated the critical need of balanced fertilisation in enhancing the performance of wheat (*Triticum aestivum* L. cv. PBW 826) within the rice-wheat system on sandy loam soil. The fully recommended nitrogen, phosphorus and potassium (NPK) dosage (M_1) consistently resulted in the greatest growth, physiological efficiency and yield, achieving a 47 % increase in GY (56.00 q ha^{-1}) compared to nutrient-deficient treatments, attributable to improved meristem activity, nutrient absorption and sink formation. The 50 % biochar + 50 % FYM blend (T_4) emerged as the most effective organic amendment, enhancing growth and physiological parameters by 10–25 % and increasing yield by 14 % compared to the control (50.13 q ha^{-1}) due to improved nutrient retention, moisture preservation, and microbial activity. Although interactions were not statistically significant, $M_1 + T_4$ exhibited additive effects, achieving peak production (56.00 q ha^{-1} grain, 78.40 q ha^{-1} straw). The combined application of balanced NPK with a 50:50 biochar-FYM mixture improves crop performance, maintains soil fertility, utilises rice wastes, and promotes resilience and environmental sustainability in Punjab's nutrient-deficient rice-wheat agroecosystems.

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Authors' contributions

BPK conceptualised the study, curated the data, performed formal analysis and statistical analysis, carried out the investigation, developed the methodology and wrote the original draft as well as contributed to the review and editing of the manuscript. RT curated the data, performed formal analysis, carried out the investigation, contributed to the methodology and wrote the original draft. RKG and CMM curated the data, performed formal analysis, carried out the investigation, contributed to the methodology and statistical analysis and participated in the review and editing of the manuscript. All authors 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 ChatGPT and perplexity in order to improve, the authors used ChatGPT and perplexity to improve the readability and language of the work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Sharma K, Sharma PK. Wheat as a nutritional powerhouse: Shaping global food security. In: Meena VS, Jaiswal JP, Jinger D, Paramesh V, editors. *Triticum – The Pillar of Global Food Security*. London: IntechOpen; 2025. <https://doi.org/10.5772/intechopen.1009499>
- Singh SK, Beillard MJ. Grain and Feed Annual 2024 [Internet]. New Delhi: USDA Foreign Agricultural Service (FAS); 2024. Report No.: IN2024-0016.
- Briak H, Kebede F. Wheat (*Triticum aestivum*) adaptability evaluation in a semi-arid region of Central Morocco using APSIM model. *Sci Rep*. 2021;11(1):23173. <https://doi.org/10.1038/s41598-021-02668-3>
- Dhawan V, Singh JM, Kashish. Commercialization to specialization: a scenario of Punjab agriculture. *Econ Aff*. 2015;60(3):433–7. <https://doi.org/10.5958/0976-4666.2015.00061.3>
- Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Singh B, et al. How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Res*. 2003;81(2–3):159–80. [https://doi.org/10.1016/S0378-4290\(02\)00219-8](https://doi.org/10.1016/S0378-4290(02)00219-8)
- Ghosh T, Das B, Chakraborty D, Singh VK, Das D, Aggarwal P, et al. Evaluation of soil quality frameworks in rice–wheat systems under integrated nutrient management in Indo-Gangetic plains. *Sci Rep*. 2025;15:37511. <https://doi.org/10.1038/s41598-025-21630-1>
- Saini N, Kaur S, Dhaliwal SS, Singh S, Sharma H. Assessment of soil organic carbon stocks in relation to variation in physiography under sub-mountainous Shiwalik ranges of lower Himalayas, India. *Carbon Manag*. 2021;12(3):265–73. <https://doi.org/10.1080/17583004.2021.1910901>
- Singh S, Benbi DK. Punjab-soil health and green revolution: a quantitative analysis of major soil parameters. *J Crop Improv*. 2016;30(3):323–40. <https://doi.org/10.1080/15427528.2016.1157540>
- De Oliveira Silva A, Jaenisch BR, Ciampitti IA, Lollato RP. Wheat nitrogen, phosphorus, potassium, and sulfur uptake dynamics under different management practices. *Agron J*. 2021;113(3):2752–69. <https://doi.org/10.1002/agj2.20637>
- An YM, Song LL, Liu YR, Shu YJ, Guo CH. De novo transcriptional analysis of alfalfa in response to saline-alkaline stress. *Front Plant Sci*. 2016;7:931. <https://doi.org/10.3389/fpls.2016.00931>
- Li E, Tang J, Liu J, Zhang Z, Hua B, Jiang J, et al. The roles of hormone signals involved in rhizosphere pressure response induce corm expansion in *Sagittaria trifolia*. *Int J Mol Sci*. 2023;24(15):12345. <https://doi.org/10.3390/ijms241512345>
- Ragel P, Raddatz N, Leidi EO, Quintero FJ, Pardo JM. Regulation of K⁺ nutrition in plants. *Front Plant Sci*. 2019;10:281. <https://doi.org/10.3389/fpls.2019.00281>
- Deng Y, Zhang Y, Lu Y, Lu K, Bai H, Ren H. Metabolomics evaluation of the in vivo toxicity of bromoacetonitriles: one class of high-risk nitrogenous disinfection byproducts. *Sci Total Environ*. 2017;579:107–14. <https://doi.org/10.1016/j.scitotenv.2016.11.003>
- Paramesh V, Mohan Kumar R, Rajanna GA, Gowda S, Nath AJ, Madival Y, et al. Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Front Sustain Food Syst*. 2023;7:1173258. <https://doi.org/10.3389/fsufs.2023.1173258>
- Chahal HS, Singh A, Dhillon IS, Kaur J. Farmyard manure: a boon for integrated nutrient management. *Int J Agric Environ Biotechnol*. 2020;13(4):483–95. <https://doi.org/10.30954/0974-1712.04.2020.14>
- Nguyen HT, Aviso KB, Le DQ, Kojima N, Tokai A. A linear programming input–output model for mapping low-carbon scenarios for Vietnam in 2030. *Sustain Prod Consum*. 2018;16:134–40. <https://doi.org/10.1016/j.spc.2018.07.004>
- Khan SAR, Jian C, Zhang Y, Golpira H, Kumar A, Sharif A. Environmental, social and economic growth indicators spur logistics performance: from the perspective of South Asian Association for Regional Cooperation countries. *J Clean Prod*. 2019;214:1011–23. <https://doi.org/10.1016/>

[j.jclepro.2018.12.322](https://doi.org/10.1016/j.jclepro.2018.12.322)

18. Blanco-Canqui H. Biochar and soil physical properties. *Soil Sci Soc Am J*. 2017;81(4):687–711. <https://doi.org/10.2136/sssaj2017.01.0017>
19. Zhang M, Riaz M, Zhang L, El-Desouki Z, Jiang C. Biochar induces changes to basic soil properties and bacterial communities of different soils to varying degrees at 25 mm rainfall: more effective on acidic soils. *Front Microbiol*. 2019;10:1321. <https://doi.org/10.3389/fmicb.2019.01321>
20. Giri A, Banerjee UC, Kumar M, Pant D. Intracellular carbonic anhydrase from *Citrobacter freundii* and its role in bio-sequestration. *Bioresour Technol*. 2018;267:789–92. <https://doi.org/10.1016/j.biortech.2018.07.089>
21. Lohan SK, Jat HS, Yadav AK, Sidhu HS, Jat ML, Choudhary M, et al. Burning issues of paddy residue management in north-west states of India. *Renew Sustain Energy Rev*. 2018;81(Pt 1):693–706. <https://doi.org/10.1016/j.rser.2017.08.057>
22. Richards S, Paterson E, Withers PJA, Stutter M. The contribution of household chemicals to environmental discharges via effluents: combining chemical and behavioural data. *J Environ Manage*. 2015;150:427–34. <https://doi.org/10.1016/j.jenvman.2014.12.023>
23. Zhang Z, Xie M, Dai X, Duan Z, Lu Z, Cai L, et al. The prognostic value and economic benefits of coronary angiography-derived fractional flow reserve-guided strategy in patients with coronary artery disease. *Heliyon*. 2023;9(6):e17464. <https://doi.org/10.1016/j.heliyon.2023.e17464>
24. Jaswal A, Mehta CM, Singh A. Probing the impact of biochar combined with organic and inorganic amendments on soil carbon pools of rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. *Res Crops*. 2022;23:508–15. <https://doi.org/10.31830/24541761.2022.roc-861>
25. Kaur H, Gill RS, Dheri GS. Response of wheat to potassium and its fractions in Punjab soils. *Indian J Agric Sci*. 2021;91(4):629–33. <https://doi.org/10.56093/ijas.v91i4.112729>
26. Watson DJ. Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Ann Bot*. 1947;11(41):41–76. <https://doi.org/10.1093/oxfordjournals.aob.a083148>
27. Arnon DI. Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. *Plant Physiol*. 1949;24(1):1–15. <https://doi.org/10.1104/pp.24.1.1>
28. Barrs HD, Weatherley PE. A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Aust J Biol Sci*. 1962;15(3):413–28. <https://doi.org/10.1071/B19620413>
29. Premachandra GS, Saneoka H, Ogata S. Cell membrane stability, an indicator of drought tolerance, as affected by applied nitrogen in soyabean. *J Agric Sci*. 1990;115(1):63–6. <https://doi.org/10.1017/S0021859600073925>
30. Panse VG, Sukhatme PV. Statistical methods for agricultural workers. 4th ed. New Delhi: ICAR; 1985.
31. Zeng J, Sheng H, Liu Y, Wang Y, Wang Y, Kang H, et al. High nitrogen supply induces physiological responsiveness to long photoperiod in barley. *Front Plant Sci*. 2017;8:569. <https://doi.org/10.3389/fpls.2017.00569>
32. Yang D, Cai T, Luo Y, Wang Z. Optimizing plant density and nitrogen application to manipulate tiller growth and increase grain yield and nitrogen-use efficiency in winter wheat. *PeerJ*. 2019;7:e6484. <https://doi.org/10.7717/peerj.6484>
33. Ali A, Jabeen N, Chachar Z, Chachar S, Ahmed S, Ahmed N, et al. The role of biochar in enhancing soil health and interactions with rhizosphere properties and enzyme activities in organic fertiliser substitution. *Front Plant Sci*. 2025;16:1595208. <https://doi.org/10.3389/fpls.2025.1595208>
34. Zhai L, Xie R, Wang P, Liu G, Fan P, Li S. Impact of recent breeding history on the competitiveness of Chinese maize hybrids. *Field Crops Res*. 2016;191:75–82. <https://doi.org/10.1016/j.fcr.2016.02.017>
35. Eliášová K, Vondráková Z, Gemperlová L, Neděla V, Runštuk J, Fischerová L, et al. The response of *Picea abies* somatic embryos to UV-B radiation depends on the phase of maturation. *Front Plant Sci*. 2018;9:1736. <https://doi.org/10.3389/fpls.2018.01736>
36. Abbas K, Javed M, Aslam S, Butt FR, Al-Ansari MM, Elshikh MS, et al. Co-application of potassium and thiourea for mitigating salinity stress in wheat seedlings. *Sci Rep*. 2025;15:14689. <https://doi.org/10.1038/s41598-025-98878-0>
37. Morton SK, Rodriguez AJ, Morris DR, Bhandari AP, Moxon JV, Golledge J. A systematic review and meta-analysis of circulating biomarkers associated with failure of arteriovenous fistulae for haemodialysis. *PLoS One*. 2016;11(7):e0159963. <https://doi.org/10.1371/journal.pone.0159963>
38. Cakmak I. The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *J Plant Nutr Soil Sci*. 2005;168(4):521–30. <https://doi.org/10.1002/jpln.200420485>
39. Epstein E. Silicon. *Annu Rev Plant Physiol Plant Mol Biol*. 1999;50:641–64. <https://doi.org/10.1146/annurev.arplant.50.1.641>
40. Sala G, Pasta S, Maggio A, La Mantia T. *Sambucus nigra* L. (fam. Viburnaceae) in Sicily: distribution, ecology, traditional use and therapeutic properties. *Plants (Basel)*. 2023;12(19):3457. <https://doi.org/10.3390/plants12193457>
41. Yang Y, Liu B, Ni X, Tao L, Yu L, Yang Y, et al. Rice productivity and profitability with slow-release urea containing organic–inorganic matrix materials. *Pedosphere*. 2021;31(4):511–20. [https://doi.org/10.1016/S1002-0160\(21\)60001-2](https://doi.org/10.1016/S1002-0160(21)60001-2)
42. Krishnasamy K, Bell R, Ma Q. Wheat responses to sodium vary with potassium use efficiency of cultivars. *Front Plant Sci*. 2014;5:631. <https://doi.org/10.3389/fpls.2014.00631>
43. Li C, Shi Y, Yu Z, Zhang Y, Zhang Z. Optimizing nitrogen application strategies can improve grain yield by increasing dry matter translocation, promoting grain filling, and improving harvest indices. *Front Plant Sci*. 2025;16:1565446. <https://doi.org/10.3389/fpls.2025.1565446>
44. Thornburg TE, Liu J, Li Q, Xue H, Wang G, Li L, et al. Potassium deficiency significantly affected plant growth and development as well as microRNA-mediated mechanism in wheat (*Triticum aestivum* L.). *Front Plant Sci*. 2020;11:1219. <https://doi.org/10.3389/fpls.2020.01219>
45. Khan MA, Basir A, Fahad S, Adnan M, Saleem MH, Iqbal A, et al. Biochar optimizes wheat quality, yield, and nitrogen acquisition in low fertile calcareous soil treated with organic and mineral nitrogen fertilisers. *Front Plant Sci*. 2022;13:879788. <https://doi.org/10.3389/fpls.2022.879788>
46. Frimpong KA, Abban-Baidoo E, Marschner B. Can combined compost and biochar application improve the quality of a highly weathered coastal savanna soil? *Heliyon*. 2021;7(5):e06981. <https://doi.org/10.1016/j.heliyon.2021.e07089>
47. Tokas D, Singh S, Yadav R, Kumar P, Sharma S, Singh AN. Wheat-paddy straw biochar: an ecological solution of stubble burning in the agroecosystems of Punjab and Haryana region, India, a synthesis. *Appl Ecol Environ Sci*. 2021;9(6):613–25. <https://doi.org/10.12691/aees-9-6-6>

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