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RESEARCH ARTICLE

Precision nitrogen management enhances maize productivity, efficiency and soil health in the trans-gangetic plains

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Abstract

This study evaluates real-time nitrogen (N) management using the leaf color chart (LCC) and chlorophyll content meter (CCM) on maize (*Zea mays* L.) yield, nitrogen use efficiency and soil health in Punjab's Trans-Gangetic Plains. A split-plot field experiment with three maize varieties (PMH-14, PMH-13, ADV-9293) and six N-management strategies-including LCC and CCM threshold-based applications, nano-nitrogen blends and recommended dose fertilizer regimes-was conducted with three replications during the 2024 *Kharif* season. Key findings reveal that synchronizing N supply with crop demand via CCM-50 and LCC-5 significantly enhances soil nitrogen content, soil enzymatic activities (urease, dehydrogenase and alkaline phosphatase enzymes) and organic carbon. The PMH-14 variety paired with CCM-50 delivered the highest yields (up to 9.26 t/ha), cob girth, test weight, grains per cob and plant growth parameters. Precision N management enhanced resource use efficiency and reduced fertilizer inputs by 25-50 % compared with conventional practices and increased farmer profitability. Soil properties, including pH, electrical conductivity and macronutrients, remained stable, while real-time N regimes promoted greater crops and soil resilience. Economic analysis indicated superior net returns for sensor-based interventions. The results support integrating sensor-guided N management with responsive genotypes for sustainable, climate-smart maize intensification. Multi-location validation is recommended to further refine these approaches.

Keywords: chlorophyll content meter; leaf color chart; maize; precision nitrogen management; soil health; yield efficiency

Introduction

Maize (*Zea mays* L.), the major cereal crop, underpins global food, feed and industrial demand and India is among the top producers by acreage, harvesting 34.6-37.7 million tonnes in 2023-24 according to official and market-outlook estimates, despite seasonal variability (1). India's maize area in 2023-24 was about 108.9 lakh ha, with 78.8 % during *Kharif*; major *Kharif* states by area include Madhya Pradesh, Karnataka, Rajasthan and Maharashtra, while Bihar, Maharashtra and Tamil Nadu dominate the *Rabi* area (2). By production, the leading states in 2023-24 included Karnataka (~54.9-57.1 lakh tonnes), Bihar (~56.3 lakh tonnes) and Madhya Pradesh (~43.3 lakh tonnes), alongside Tamil Nadu, Telangana, Uttar Pradesh and West Bengal. Maize productivity in India remains constrained by spatial and temporal nutrient imbalances and low nitrogen use efficiency (NUE), necessitating real-time nitrogen management approaches that synchronize nitrogen supply precisely with crop demand. (4).

Decision-support tools such as the LCC and CCM/SPAD enable real-time monitoring of crop nitrogen status, helping to synchronize fertilizer application with crop demand. This reduces nitrogen waste while sustaining or improving crop yields (5). Field studies across Indian states demonstrate that LCC- or CCM-based nitrogen management can reduce fertilizer use by 25-50 % without yield penalties, while improving nitrogen use efficiency and farm profitability. Sensor-based tools such as the GreenSeeker have further validated the benefits of in-season nitrogen correction in Indo-Gangetic cropping systems (6, 7). In parallel, sensor-based approaches (e.g., GreenSeeker) validated in the northwestern Indo-Gangetic Plains demonstrate that need-based, in-season N corrections improve N uptake and recovery efficiency by aligning N with canopy vigor-a principle transferable to maize in Punjab's irrigated systems (5). Together, these real-time strategies provide a quantitative pathway to raise NUE and profitability while curbing loss pathways and environmental risk (8).

Beyond yield benefits, precision nitrogen management stabilizes soil pH, enhances soil organic carbon and stimulates biological activity, positioning it as a climate-smart approach with significant long-term sustainability potential (9-11). However, limited research exists on integrating LCC and CCM-based N management with different maize hybrids under Punjab's Trans-Gangetic Plains, where maize is vital for crop diversification (12). This study evaluates the impact of precision N tools on soil chemical and biological properties, plant growth, yield attributes and economic returns, aiming to identify genotype-management combinations for sustainable maize intensification (11, 12).

Materials and Methods

Site description

The experiment was conducted during the *Kharif* season of 2024 at the Agricultural Research Farm, Lovely Professional University, Phagwara, Punjab, India (31°14′43.8″ N, 75°41′44.1″ E; 252 m AMSL). The site is in the Trans-Gangetic Plains agro-climatic zone, with a sandy loam soil (41 % sand, 25.1 % silt, 32.9 % clay), pH 7.3, EC 0.23 mmhos cm^{-1} and 0.45 % organic carbon. Initial soil nutrient status was 237.3 kg/ha N, 24.7 kg/ha P and 217.8 kg/ha K.

Experimental design

A split-plot design was adopted with three replications. Main plots comprised three maize hybrids: PMH-14, PMH-13 and ADV-9293. Sub-plots received six nitrogen management treatments:

- T_1: Leaf color chart (LCC) 4
- T_2: LCC 5
- T_3: Chlorophyll content meter (CCM) 40
- T_4: CCM 50
- T_5: 50 % nano N + 50 % inorganic N
- T_6: 100 % recommended dose fertilizer (RDF; 120:30:30 kg/ha N:P:K)

Plot size was 3 m × 5 m. Sowing occurred in late June at 60 cm row and 20 cm plant spacing. Phosphorus and potassium were applied basally; nitrogen applications followed treatment protocols. For LCC and CCM treatments, N was applied when leaf color intensity fell below threshold values (LCC 4 or 5, CCM 40 or 50 units). T_5 received nano and conventional N sources, T_6 followed standard splits (basal, knee-high, tasseling).

Data collection

Five plants per plot were tagged for plant height, leaf number and leaf area at 30, 60 and harvest DAS (days after sowing). Leaf area was measured on the third leaf from the top. Dry matter yield was determined by oven-drying harvested plants at 60 °C. Soil samples (0-15 cm) were collected before sowing and after harvest and analyzed for pH, electrical conductivity (EC), organic carbon, available nitrogen (N), phosphorus (P) and potassium (K) (13-17).

Yield parameters included cobs/plant, cob length/girth (digital caliper), average cob weight, test weight (1000 kernel, 12 % moisture), grain and stover yield (adjusted to standard moisture) (10). Soil enzyme activities (urease, dehydrogenase and alkaline phosphatase) were determined following standard protocols.

Data analysis

Data was compiled in Microsoft Excel and analysis of variance (ANOVA) was conducted using OPSTAT software (HAU, Hisar). Mean differences were tested at the 5 % probability level ($P < 0.05$). Results are presented with standard error of the mean (SE± m) and critical difference (CD) values.

Results

Soil chemical properties

Soil pH was significantly influenced by the maize variety, with PMH14 maintaining higher pH values than PMH13 and ADV9293 across growth stages (Table 1). Nutrient management did not significantly affect soil pH. However, varieties did not significantly affect soil electrical conductivity or soil organic carbon at any stage. In contrast, the sub-plot treatments (nutrient management practices) had no significant effect on soil pH at any growth stage despite numerical variations. For soil EC, sub-plot effects were significant at 60 DAS and harvest, with CCM 50 recording the highest values (0.44 and 0.40 dS/m, respectively), significantly surpassing CCM 40 (0.32 and 0.30 dS/m), RDF (0.35 and 0.32 dS/m) and other treatments, while LCC treatments maintained intermediate values (Table 2). Similarly, soil organic carbon was significantly enhanced by CCM 50 at 60 DAS (0.36 %) and harvest (0.32 %), outperforming all other nutrient management practices including RDF, LCC treatments and organic-inorganic combinations, which clustered around 0.25-0.30 % (Table 3). Soil EC and OC were significantly enhanced under the CCM 50 treatment, particularly when combined with the ADV-9293 variety, which exhibited the highest EC and SOC values at 60 DAS (Table 2.1, 3.1).

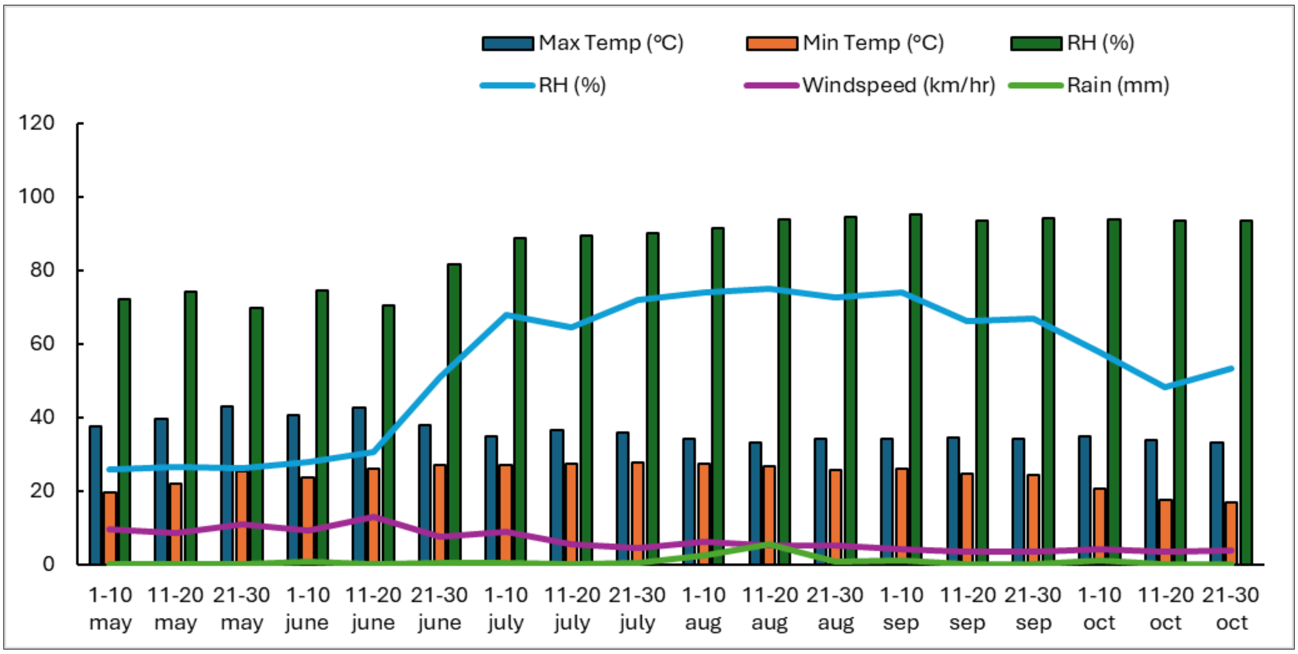

Fig. 1. Weekly meteorological data during the 2024 *Kharif* season.

Table 1. Effect of LCC AND CCM based nitrogen management on soil pH at different growth stages

Soil PH			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	8.15	8.00	7.95
PMH13	7.99	7.86	7.81
ADV9293	7.88	7.74	7.71
SE (m) ±	0.04	0.04	0.04
CD at 5 %	0.17	0.16	0.15
Sub-plot			
(LCC) 4	8.04	7.93	7.92
(LCC) 5	8.05	7.90	7.86
(CCM) 40	8.03	7.92	7.90
(CCM) 50	7.96	7.77	7.74
50 % (organic) + 50 % (inorganic)	7.99	7.89	7.76
100 % (RDF)	7.95	7.78	7.75
SE (m) ±	0.07	0.07	0.07
CD at 5 %	NS	NS	NS
Main × Sub (interaction)			
SE (m) ±	0.11	0.12	0.12
CD at 5 %	NS	NS	NS

Table 2. Effect of LCC AND CCM based nitrogen management on soil EC (dS/m) at different growth stages

Soil EC (dS/m)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	0.35	0.37	0.34
PMH13	0.34	0.36	0.34
ADV9293	0.34	0.39	0.35
SE (m) ±	0.01	0.01	0.01
CD at 5 %	NS	NS	NS
Sub-plot			
(LCC) 4	0.36	0.38	0.35
(LCC) 5	0.37	0.39	0.36
(CCM) 40	0.31	0.32	0.30
(CCM) 50	0.35	0.44	0.40
50 % (organic) + 50 % (inorganic)	0.35	0.37	0.33
100 % (RDF)	0.33	0.35	0.32
SE (m) ±	0.02	0.02	0.02
CD at 5 %	NS	0.05	0.05
Main × Sub (interaction)			
SE (m) ±	0.03	0.03	0.03
CD at 5 %	NS	0.08	0.08

Table 2.1 Interaction effect of LCC AND CCM based nitrogen management on soil EC at 60 days after sowing (DAS)

(Interaction) 60 DAS				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	0.40	0.36	0.38	0.38
(LCC) 5	0.41	0.40	0.38	0.39
(CCM) 40	0.35	0.26	0.36	0.32
(CCM) 50	0.37	0.38	0.56	0.44
50 % (organic) + 50 % (inorganic)	0.37	0.35	0.38	0.37
100 % (RDF)	0.35	0.40	0.30	0.35
Mean	0.37	0.36	0.39	
SE (m) ±		0.03		
CD at 5 %		0.08		

Table 2.2 Interaction effect of nutrient management practices on soil electrical conductivity (EC) at harvest stage

(Interaction) Harvest				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	0.35	0.35	0.36	0.35
(LCC) 5	0.37	0.36	0.34	0.36
(CCM) 40	0.32	0.24	0.34	0.30
(CCM) 50	0.33	0.35	0.52	0.40
50 % (organic) + 50 % (inorganic)	0.32	0.38	0.28	0.33
100 % (RDF)	0.32	0.37	0.27	0.32
Mean	0.34	0.34	0.35	
SE (m) ±		0.03		
CD at 5 %		0.08		

Table 3. Effect of LCC AND CCM based nitrogen management on soil organic carbon (%) at different growth stages

SOC (%)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	0.28	0.30	0.26
PMH13	0.26	0.28	0.25
ADV9293	0.27	0.32	0.29
SE (m) +	0.01	0.01	0.01
CD at 5 %	NS	NS	NS
Sub-plot			
(LCC) 4	0.28	0.30	0.27
(LCC) 5	0.27	0.29	0.25
(CCM) 40	0.25	0.27	0.25
(CCM) 50	0.27	0.36	0.32
50 % (organic) + 50 % (inorganic)	0.27	0.29	0.26
100 % (RDF)	0.26	0.28	0.25
SE (m) +	0.01	0.01	0.01
CD at 5 %	NS	0.04	0.03
Main × sub (interaction)			
SE (m) ±	0.02	0.02	0.02
CD at 5 %	NS	0.06	0.06

Table 3.1 Interaction effect of nutrient management practices on soil organic carbon (SOC %) at 60 days after sowing (DAS)

(Interaction) 60 DAS				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	0.30	0.30	0.29	0.30
(LCC) 5	0.27	0.29	0.29	0.29
(CCM) 40	0.31	0.22	0.28	0.27
(CCM) 50	0.29	0.31	0.48	0.36
50 % (organic) + 50 % (inorganic)	0.32	0.26	0.30	0.29
100 % (RDF)	0.30	0.27	0.27	0.28
Mean	0.30	0.28	0.32	
SE (m) +		0.06		
CD at 5 %		0.02		

Table 3.2 Interaction effect of nutrient management practices on soil organic carbon (SOC %) at harvest stage

(Interaction) Harvest				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	0.25	0.29	0.27	0.27
(LCC) 5	0.23	0.26	0.26	0.25
(CCM) 40	0.29	0.20	0.26	0.25
(CCM) 50	0.25	0.27	0.44	0.32
50 % (organic) + 50 % (inorganic)	0.27	0.25	0.25	0.26
100 % (RDF)	0.27	0.24	0.24	0.25
Mean	0.26	0.25	0.29	
CD at 5 %		0.02		
SE (m) ±		0.06		

Soil nutrient status

Among the maize varieties evaluated, PMH14 consistently retained more soil nitrogen than PMH13 and ADV9293 across all growth stages. Among nutrient management treatments, CCM 50 and LCC 5 consistently maintained higher soil nitrogen levels compared to RDF and organic-inorganic blends (Table 4). No significant differences in phosphorus and potassium content were observed across varieties or treatments (Tables 5, 6). Interaction effects between variety and nutrient management were significant for soil nitrogen status at all growth stages (Table 4.1-4.3).

The combination of PMH-14 with CCM 50 consistently produced the highest soil nitrogen content (198.40 kg/ha at 30 DAS, 203.10 kg/ha at 60 DAS and 200.20 kg/ha at harvest), followed closely by combinations of PMH-14 with LCC 5 (198.13, 202.43 and 199.73 kg/ha) and CCM 40 (197.43, 201.43, 198.83 kg/ha). In contrast, the lowest nitrogen accumulation occurred in the ADV-9293 hybrid when paired with the 50 % organic plus 50 % inorganic treatment (182.35, 184.05 and 183.25kg/ha across the three stages). Intermediate results were generally observed for the 100 % RDF combinations. The data suggest that synchronizing nitrogen application through decision -support tools (CCM/LCC) with high-responsiveness varieties like PMH-14 optimizes soil nitrogen retention, while neither variety nor fertilization approach significantly influenced phosphorus or potassium levels.

Soil biological activity

Among the maize varieties (main plot), PMH-14 consistently exhibited the highest urease activity at all growth stages, recording values of 0.47, 0.48 and 0.37 µg NH_4^+-N g^{-1} soil h^{-1} at 30 DAS, 60 DAS and harvest, respectively (Table 7). PMH-13 showed intermediate urease activity, while ADV-9293 had the lowest values, indicating significant varietal effects on nitrogen mineralization potential. Dehydrogenase activity also showed a similar trend, with PMH-14 displaying the highest microbial activity (0.25, 0.36 and 0.37 µg TPF g^{-1} soil h^{-1}), significantly exceeding that of PMH-13 and ADV-9293 (Table 8). Alkaline phosphatase activity was highest in PMH-14 across all stages, again demonstrating its superior potential to mobilize phosphorus in the soil (Table 9).

Table 4. Effect of LCC AND CCM based nitrogen management on nitrogen (mg/kg) at different growth stages

Nitrogen (kg/ha)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	196.66	200.74	198.19
PMH13	193.77	197.24	195.77
ADV9293	189.02	191.54	190.45
SE (m) ±	1.22	1.35	1.29
CD at 5 %	4.78	5.32	5.06
Sub-plot			
(LCC) 4	192.23	195.63	194.43
(LCC) 5	195.01	198.58	196.64
(CCM) 40	194.67	198.14	196.30
(CCM) 50	195.19	198.92	196.79
50 % (organic) + 50 % (inorganic)	189.99	192.86	191.36
100 % (RDF)	191.81	194.91	193.31
SE (m) ±	0.83	0.86	0.91
CD at 5 %	2.39	2.49	2.61
Main × Sub (interaction)			
SE (m) ±	1.43	1.49	1.57
CD at 5 %	4.14	4.32	4.53

Table 4.1 Interaction effect of nutrient management practices on nitrogen at 30 days after sowing (DAS)

(Interaction) 30DAS				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	196.23	193.58	186.88	192.23
(LCC) 5	198.13	194.09	192.81	195.01
(CCM) 40	197.43	193.90	192.67	194.67
(CCM) 50	198.40	194.19	192.97	195.19
50 % (organic) + 50 % (inorganic)	194.23	193.39	182.35	189.99
100 % (RDF)	195.53	193.46	186.45	191.81
Mean	196.66	193.77	189.02	
SE (m) ±		1.43		
CD at 5 %		4.14		

Table 4.2 Interaction effect of nutrient management practices on nitrogen at 60 Days after sowing (DAS)

(Interaction) 60 DAS				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	200.13	197.08	189.68	195.63
(LCC) 5	202.43	197.69	195.61	198.58
(CCM) 40	201.43	197.50	195.47	198.14
(CCM) 50	203.10	197.89	195.77	198.92
50 % (organic) + 50 % (inorganic)	198.03	196.49	184.05	192.86
100 % (RDF)	199.33	196.76	188.65	194.91
Mean	200.74	197.24	191.54	
SE (m) ±		1.49		
CD at 5 %		4.32		

Table 4.3 Interaction effect of nutrient management practices on nitrogen at harvest stage

(Interaction) HARVEST				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	197.63	197.08	188.58	194.43
(LCC) 5	199.73	195.79	194.41	196.64
(CCM) 40	198.83	195.70	194.37	196.30
(CCM) 50	200.20	195.79	194.37	196.79
50 % (organic) + 50 % (inorganic)	195.73	195.09	183.25	191.36
100 % (RDF)	197.03	195.16	187.75	193.31
Mean	198.19	195.77	190.45	
SE (m) ±		1.57		
CD at 5 %		4.53		

Table 5. Effect of LCC AND CCM based nitrogen management on phosphorus (kg/ha) at different growth stages

Phosphorus (kg/ha)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	20.98	25.24	25.78
PMH13	20.46	24.96	25.03
ADV9293	20.04	25.08	24.49
SE (m) ±	0.18	0.19	0.31
CD at 5 %	NS	NS	NS
Sub-plot			
(LCC) 4	20.52	24.43	25.05
(LCC) 5	20.65	24.98	25.29
(CCM) 40	20.54	25.22	25.16
(CCM) 50	20.77	25.93	25.66
50 % (organic) + 50 % (inorganic)	20.08	24.86	24.42
100 % (RDF)	20.42	25.12	25.03
SE (m) ±	0.29	0.36	0.38
CD at 5 %	NS	NS	NS
Main × Sub (interaction)			
SE (m) ±	0.51	0.62	0.65
CD at 5 %	NS	NS	NS

Table 6. Effect of LCC AND CCM based nitrogen management on potassium (kg/ha) at different growth stages

Potassium (Kg/ha)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	181.58	183.81	182.77
PMH13	179.40	181.87	180.26
ADV9293	177.41	179.04	178.07
SE (m) ±	0.36	0.56	0.58
CD at 5 %	1.43	2.18	2.29
Sub-plot			
(LCC) 4	179.11	181.30	179.87
(LCC) 5	180.32	182.01	180.86
(CCM) 40	179.70	181.87	180.58
(CCM) 50	180.58	182.26	181.89
50 % (organic) + 50 % (inorganic)	178.20	180.89	179.44
100 % (RDF)	178.88	181.12	179.57
SE (m) ±	0.99	1.06	0.93
CD at 5 %	NS	NS	NS
Main × Sub (interaction)			
SE (m) ±	1.71	1.83	1.62
CD at 5 %	NS	NS	NS

Table 7. Effect of LCC AND CCM based nitrogen management on urease (µmol) at different growth stages

Urease (µg NH_4^+-N g^{-1} soil hr^{-1})			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	0.47	0.48	0.37
PMH13	0.43	0.39	0.28
ADV9293	0.30	0.29	0.22
SE (m) ±	0.01	0.01	0.01
CD at 5 %	0.03	0.02	0.02
Sub-plot			
(LCC) 4	0.39	0.37	0.27
(LCC) 5	0.42	0.41	0.33
(CCM) 40	0.41	0.39	0.30
(CCM) 50	0.43	0.43	0.34
50 % (organic) + 50 % (inorganic)	0.36	0.36	0.25
100 % (RDF)	0.38	0.37	0.26
SE (m) ±	0.01	0.00	0.01
CD at 5 %	0.02	0.01	0.03
Main × Sub (interaction)			
SE (m) ±	0.01	0.004	0.02
CD at 5 %	0.03	0.01	0.06

Table 7.1 Interaction effect of nutrient management practices on urease at 30 days after sowing (DAS)

(Interaction) 30 DAS				
	PMH14	PMH13	ADV9293	Mean
(LCC) 4	0.47	0.43	0.26	0.39
(LCC) 5	0.47	0.45	0.33	0.42
(CCM) 40	0.47	0.44	0.32	0.41
(CCM) 50	0.49	0.45	0.36	0.43
50 % (Organic) + 50 % (Inorganic)	0.46	0.38	0.25	0.36
100 % (RDF)	0.46	0.42	0.26	0.38
Mean	0.47	0.43	0.30	
SE (m) ±			0.03	
CD at 5 %			0.01	

Table 7.2 Interaction effect of nutrient management practices on urease at 60 days after sowing (DAS)

(Interaction) 60 DAS				
	PMH14	PMH13	ADV9293	Mean
(LCC) 4	0.48	0.36	0.28	0.37
(LCC) 5	0.49	0.43	0.31	0.41
(CCM) 40	0.49	0.39	0.29	0.39
(CCM) 50	0.50	0.46	0.33	0.43
50 % (Organic) + 50 % (Inorganic)	0.46	0.34	0.27	0.36
100 % (RDF)	0.47	0.35	0.28	0.37
Mean	0.48	0.39	0.29	
SE (m) ±			0.004	
CD at 5 %			0.01	

Table 7.3 Interaction effect of nutrient management practices on urease at harvest

(Interaction) Harvest				
	PMH14	PMH13	ADV9293	Mean
(LCC) 4	0.33	0.28	0.19	0.27
(LCC) 5	0.45	0.29	0.26	0.33
(CCM) 40	0.35	0.28	0.26	0.30
(CCM) 50	0.48	0.29	0.26	0.34
50 % (organic) + 50 % (inorganic)	0.32	0.26	0.16	0.25
100 % (RDF)	0.33	0.28	0.17	0.26
Mean	0.37	0.28	0.22	
SE (m) ±			0.02	
CD at 5 %			0.06	

Table 8. Effect of LCC AND CCM based nitrogen management on dehydrogenase (µg) at different growth stages

Dehydrogenase (µg TPF g^{-1} soil h^{-1})			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	0.25	0.36	0.37
PMH13	0.22	0.32	0.30
ADV9293	0.14	0.25	0.22
SE (m) ±	0.01	0.01	0.02
CD at 5 %	0.06	0.03	0.06
Sub-plot			
(LCC) 4	0.20	0.29	0.28
(LCC) 5	0.21	0.33	0.33
(CCM) 40	0.21	0.32	0.30
(CCM) 50	0.22	0.37	0.35
50 % (organic) + 50 % (inorganic)	0.19	0.27	0.26
100 % (RDF)	0.19	0.28	0.26
SE (m) ±	0.02	0.02	0.02
CD at 5 %	NS	0.05	0.05
Main × Sub (interaction)			
SE (m) ±	0.03	0.03	0.03
CD at 5 %	NS	NS	NS

Table 9. Effect of LCC AND CCM based nitrogen management on alkaline phosphatase (µmol) at different growth stages

Alkaline phosphatase (µg p-nitrophenol (pNP) g^{-1} soil h^{-1})			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	0.48	0.48	0.36
PMH13	0.41	0.44	0.32
ADV9293	0.31	0.35	0.24
SE (m) ±	0.03	0.01	0.00
CD at 5 %	0.11	0.03	0.02
Sub-plot			
(LCC) 4	0.39	0.43	0.30
(LCC) 5	0.42	0.44	0.32
(CCM) 40	0.40	0.44	0.32
(CCM) 50	0.43	0.45	0.33
50 % (organic) + 50 % (inorganic)	0.38	0.39	0.28
100 % (RDF)	0.39	0.41	0.29
SE (m) ±	0.03	0.01	0.01
CD at 5 %	NS	0.03	0.03
Main × Sub (interaction)			
SE (m) ±	0.05	0.02	0.02
CD at 5 %	NS	NS	NS

Among nutrient management treatments (sub-plot), CCM 50 consistently enhanced enzyme activities, achieving the highest urease activity (0.43, 0.43 and 0.34 µg NH_4^+-N g^{-1} soil h^{-1}), dehydrogenase activity (0.22, 0.37 and 0.35 µg TPF g^{-1} soil h^{-1}) and alkaline phosphatase activity (0.43, 0.45 and 0.33 µg p-nitrophenol g^{-1} soil h^{-1}), outperforming other treatments such as LCC 4, LCC 5, CCM 40, RDF and organic-inorganic combinations. While most parameters showed significant variation, some stages exhibited non-significant differences; however, the overall pattern reflects the enhanced microbial enzymatic activity under precise nitrogen management with CCM 50 and the superior performance of PMH-14 in stimulating soil biological functions.

Interaction analysis revealed statistically significant effects between maize varieties and nutrient management on urease activity at all growth stages, as well as for alkaline phosphatase at later stages, while interactions for dehydrogenase remained non-significant (Table 7.1 -7.3). The highest urease activity was observed in the (CCM) 40 × PMH-14 combination (0.49 µg NH_4^+-N g^{-1} soil h^{-1} at 60 DAS), outperforming others such as (CCM) 40 × ADV-9293 (0.29), which was among the lowest. Similarly, alkaline phosphatase peaked with (CCM) 40 × PMH-14 (0.45 µg p-nitrophenol g^{-1} soil h^{-1} at 60 DAS), indicating that specific variety-treatment combinations synergistically enhance soil enzymatic activity. These findings suggest that coupling high-performing maize genotypes like PMH-14 with nutrient management strategies such as CCM 50 optimizes soil biological activity, potentially benefiting soil nutrient cycling and crop nutrient availability. Conversely, combinations involving less responsive varieties and organic blends yielded lower enzyme activities, highlighting the importance of integrated genotype-nutrient management approaches.

Plant growth parameters

PMH14 achieved significantly greater plant height, leaf number and leaf area than PMH13 and ADV9293 (Table 10-12). Among nutrient management treatments, CCM 50 produced the tallest plants and largest canopies, while RDF and organic-inorganic blends showed the lowest growth. Where parameters were non-significant, observed numerical differences should be interpreted cautiously. Interaction effects between varieties and nutrient management on plant growth parameters were statistically non-significant for all recorded stages and traits, indicating that the influence of nutrient management was consistent across varieties. Despite the lack of significant interactions, numerical trends suggest that combinations of PMH-14 with CCM 50 and LCC 5 generally yielded the highest plant height (e.g., PMH-14 × CCM 50 at ~125 cm height), greatest number of leaves and largest leaf area, illustrating synergistic potential when combining responsive genotypes with precision nutrient management. Conversely, ADV-9293 combined with 50 % organic + 50 % inorganic treatments often exhibited the lowest values, reinforcing the importance of both variety selection and nutrient management for optimal growth, albeit independently.

Table 10. Effect of LCC AND CCM based nitrogen management on plant height (cm) at different growth stages

Plant height (cm)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	53.93	125.26	203.26
PMH13	46.77	111.27	189.27
ADV9293	40.49	86.28	164.28
SE (m) ±	2.78	0.90	0.92
CD at 5 %	NS	3.53	3.60
Sub-plot			
(LCC) 4	46.80	108.47	186.47
(LCC) 5	48.15	111.50	189.50
(CCM) 40	47.91	110.60	188.60
(CCM) 50	50.84	114.56	192.56
50 % (organic) + 50 % (inorganic)	43.61	98.64	176.64
100 % (RDF)	45.09	101.84	179.84
SE (m) ±	4.17	3.12	3.18
CD at 5 %	NS	9.00	9.19
Main × Sub (interaction)			
SE (m) ±	7.22	5.40	5.51
CD at 5 %	NS	NS	NS

Table 11. Effect of LCC AND CCM based nitrogen management on no. of leaves at different growth stages

No of leaves			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	7.09	12.44	15.26
PMH13	6.49	10.68	13.50
ADV9293	5.50	9.94	12.76
SE (m) ±	0.07	0.14	0.08
CD at 5 %	0.29	0.55	0.33
Sub-plot			
(LCC) 4	6.27	11.07	13.89
(LCC) 5	6.50	11.30	14.12
(CCM) 40	6.46	11.18	14.01
(CCM) 50	6.66	11.48	14.30
50 % (organic) + 50 % (inorganic)	6.10	10.28	13.10
100 % (RDF)	6.15	10.82	13.64
SE (m) ±	0.11	0.24	0.18
CD at 5 %	0.31	0.71	0.51
Main × Sub (interaction)			
SE (m) ±	0.19	0.42	0.31
CD at 5 %	NS	NS	NS

Table 12. Effect of LCC AND CCM based nitrogen management on leaf area(cm²) at different growth stages

Leaf area (cm²)			
Main plot			
Treatments	**30 DAS**	**60 DAS**	**Harvest**
PMH14	718.92	4318.27	3546.48
PMH13	716.24	4296.32	3398.89
ADV9293	714.45	4273.77	3279.71
SE (m) +	1.20	3.41	60.59
CD at 5 %	NS	13.39	NS
Sub-plot			
(LCC) 4	716.30	4293.95	3393.14
(LCC) 5	717.03	4301.80	3436.59
(CCM) 40	716.51	4297.48	3403.86
(CCM) 50	717.58	4305.42	3455.67
50 % (organic) + 50 % (inorganic)	715.74	4287.21	3374.15
100 % (RDF)	716.06	4290.84	3386.76
SE (m) +	0.46	5.04	72.21
CD at 5 %	NS	NS	NS
Main × Sub (interaction)			
SE (m) +	0.80	8.72	125.07
CD at 5 %	NS	NS	NS

Yield attributes

The yield attributes, including test weight, girth of cob, number of grains per cob and grain yield, were significantly influenced by both maize varieties and nutrient management practices (Table 13-16). Among the varieties (main plot), PMH-14 consistently outperformed others, producing the highest test weight of 47.03 g/100 seeds, cob girth of 15.76 cm, number of grains per cob at 624.89 and grain yield of 7.48 t/ha at harvest, significantly surpassing PMH-13 (38.84 g, 14.31 cm, 521.11 grains and 6.19 t/ha) and ADV-9293 (36.11 g, 12.19 cm, 439.83 grains and 5.53 t/ha) based on the respective LSD values. Regarding nutrient management (sub-plot), CCM 50 exhibited the highest efficacy, attaining a test weight of 40.93 g/100 seeds, girth of cob of 15.04 cm, grain number per cob at 592.22 and grain yield of 7.17 t/ha, statistically at par with LCC 5 (44.79 g test weight, 14.65 cm girth, 554.56 grains, 6.54 t/ha yield) and CCM 40 and significantly higher than the 50 % organic plus 50 % inorganic treatment as well as 100 % RDF.

The interaction effects between maize varieties and nutrient management practices on yield attributes-such as test weight, girth of cob, number of grains per cob and grain yield-showed significant trends for these key parameters (Table 13.1, 14.1, 15.1, 16.1). The PMH-14 genotype combined with CCM 50 (T4 × V1) consistently produced the highest values for test weight (50.91 g/100 seeds), girth of cob (16.92 cm), number of grains per cob (754.33) and grain yield (9.26 t/ha), surpassing all other genotype-treatment pairs. Conversely, the lowest performing combinations were predominantly those involving ADV-9293 paired with 50 % organic plus 50 % inorganic treatments, exhibiting substantially reduced values such as test weight (31.85 g), cob girth (10.23 cm), grain number (407.33) and yield (4.98 t/ha). Intermediate performance was observed in PMH-13 combinations and 100 % RDF treatments.

Table 13. Effect of LCC AND CCM based nitrogen management on test weight (g/100 seed) at different growth stages

Test weight (g/100 seed)	
Main plot	
Treatments	**At harvest**
PMH14	47.03
PMH13	38.84
ADV9293	36.11
SE (m) ±	1.33
CD at 5 %	5.24
Sub-plot	
(LCC) 4	42.18
(LCC) 5	44.79
(CCM) 40	41.05
(CCM) 50	40.93
50 % (organic) + 50 % (inorganic)	37.99
100 % (RDF)	37.03
SE (m) ±	1.52
CD at 5 %	4.39
Main × Sub (interaction)	
SE (m) ±	2.64
CD at 5 %	7.61

Table 13.1 Interaction effect of nutrient management practices on test weight (g/100 seed) at harvest

(Interaction) Harvest				
	PMH14	**PMH13**	**ADV9293**	**Mean**
(LCC) 4	43.44	40.37	42.74	42.18
(LCC) 5	57.80	39.75	36.83	44.79
(CCM) 40	44.75	41.29	37.10	41.05
(CCM) 50	50.91	37.10	34.78	40.93
50 % (Organic) + 50 % (Inorganic)	41.47	39.15	33.36	37.99
100 % (RDF)	43.83	35.39	31.85	37.03
Mean	47.03	38.84	36.11	
SE (m) ±		2.64		
CD at 5 %		7.61		

Table 14. Effect of LCC AND CCM based nitrogen management on girth of cob (cm) at different growth stages

Girth of cob (cm)	
Main plot	
Treatments	**At harvest**
PMH14	15.76
PMH13	14.31
ADV9293	12.19
SE (m) ±	0.14
CD at 5 %	0.56
Sub-plot	
(LCC) 4	14.06
(LCC) 5	14.65
(CCM) 40	14.30
(CCM) 50	15.04
50 % (organic) + 50 % (inorganic)	12.92
100 % (RDF)	13.53
SE (m) ±	0.12
CD at 5 %	0.36
Main × Sub (nteraction)	
SE (m) ±	0.21
CD at 5 %	0.62

Table 14.1. Interaction effect of nutrient management practices on girth of cob (cm) at harvest

	(Interaction) Harvest			
	PMH14	PMH13	ADV9293	Mean
(LCC) 4	15.39	14.28	12.49	14.06
(LCC) 5	16.35	14.69	12.91	14.65
(CCM) 40	15.69	14.49	12.73	14.30
(CCM) 50	16.92	14.86	13.34	15.04
50 % (organic) + 50 % (inorganic)	14.98	13.56	10.23	12.92
100 % (RDF)	15.22	13.95	11.42	13.53
Mean	15.76	14.31	12.19	
SE (m) ±		0.21		
CD at 5 %		0.62		

Table 15. Effect of LCC AND CCM based nitrogen management on no. of grain per cob at different growth stages

No. of grain per cob	
Main plot	
Treatments	**At harvest**
PMH14	624.89
PMH13	521.11
ADV9293	439.83
SE (m) +	16.23
CD at 5 %	63.74
Sub-plot	
(LCC) 4	513.33
(LCC) 5	554.56
(CCM) 40	530.88
(CCM) 50	592.22
50 % (organic) + 50 % (inorganic)	485.89
100 % (RDF)	494.78
SE (m) +	11.61
CD at 5 %	33.53
Main × Sub (interaction)	
SE (m) +	20.11
CD at 5 %	58.08

Table 15.1 Interaction effect of nutrient management practices on no. of grain per cob at harvest

	(Interaction) Harvest			
	PMH14	PMH13	ADV9293	Mean
(LCC) 4	588.67	517.67	433.67	513.33
(LCC) 5	663.67	537.33	462.67	554.56
(CCM) 40	618.33	530.33	443.97	530.88
(CCM) 50	754.33	547.33	475.00	592.22
50 % (organic) + 50 % (inorganic)	559.67	490.67	407.33	485.89
100 % (RDF)	564.67	503.33	416.33	494.78
Mean	624.89	521.11	439.83	
SE (m) ±		20.11		
CD at 5 %		58.08		

Table 16. Effect of LCC AND CCM based nitrogen management on grain yield (T/HA) at different growth stages

Grain yield (T/HA)	
Main plot	
Treatments	**At harvest**
PMH14	7.48
PMH13	6.19
ADV9293	5.53
SE (m) ±	0.08
CD at 5 %	0.33
Sub-plot	
(LCC) 4	6.35
(LCC) 5	6.54
(CCM) 40	6.41
(CCM) 50	7.17
50 % (organic) + 50 % (inorganic)	5.92
100 % (RDF)	5.99
SE (m) ±	0.08
CD at 5 %	0.23
Main × Sub (interaction)	
SE (m) ±	0.14
CD at 5 %	0.40

Table 16.1 Interaction effect of nutrient management practices on grain yield (T/HA) at harvest

	(Interaction) Harvest			
	PMH14	PMH13	ADV9293	Mean
(LCC) 4	7.19	6.16	5.70	6.35
(LCC) 5	7.42	6.36	5.86	6.54
(CCM) 40	7.27	6.26	5.70	6.41
(CCM) 50	9.26	6.38	5.88	7.17
50 % (organic) + 50 % (inorganic)	6.84	5.94	4.98	5.92
100 % (RDF)	6.88	6.05	5.03	5.99
Mean	7.48	6.19	5.53	6.40
SE (m) ±		0.14		
CD at 5 %		0.40		

Discussion

Our study is among the first in Punjab's Trans-Gangetic Plains to demonstrate that precision nitrogen management tools, such as the CCM and LCC, when paired with high-yielding hybrids like PMH-14, substantially improve maize yield and soil quality while reducing fertilizer inputs (18). The improvement in soil organic carbon under CCM 50 likely resulted from increased biomass production and enhanced root exudation, which in turn stimulate microbial activity and carbon sequestration, consistent with previous findings (19). This approach contrasts sharply with the pre-scheduled applications of 100 % RDF, which can lead to periods of nutrient surplus or deficit and the slower nutrient release from the 50 % organic/inorganic blend (20). Our findings align with previous research emphasizing that synchronizing N supply with crop uptake not only improves nitrogen use efficiency but also sets in motion a cascade of positive feedback loops within the soil-plant system (21).

The effectiveness of these precision N management strategies manifested clearly in the soil's chemical, biological and nutrient properties (22). The significant increase in SOC under the CCM 50 treatment, especially in interaction with the high-biomass PMH-14 variety, can be directly linked to enhanced plant growth (23). Healthier, more vigorous plants contribute greater quantities of root exudates and post-harvest residues, which are primary inputs for building SOC (24). This finding is consistent with studies that correlate higher net primary productivity with long-term carbon sequestration (25). While soil pH was largely unaffected, likely due to the soil's inherent buffering capacity and the short duration of the experiment, the significant effect on EC in the interactions highlights a nuanced outcome (26).

Increased EC under CCM 50 reflects improved nutrient availability, while remaining within non-toxic ranges. Enhanced enzyme activities such as urease, dehydrogenase and alkaline phosphatase confirm stimulated microbial nutrient cycling, consistent with earlier studies on precision nitrogen management (27).This enhanced soil environment directly fueled soil biological activity (28). The higher dehydrogenase activity observed under CCM 50 is a robust indicator of a larger, more active microbial community, fed by the increased carbon from thriving plants (29). Consequently, the activities of key nutrient-cycling enzymes-urease for nitrogen mineralization and alkaline phosphatase for phosphorus mobilization-were also significantly elevated (30). This indicates that real-time N management does not just feed the plant, but also stimulates the soil's innate capacity to supply nutrients, creating a more resilient and self-sustaining fertility system (31). The stability of soil phosphorus and potassium status across treatments further underscores that the primary driver of change in this study was nitrogen management, which did not directly alter P and K pools but created conditions for their more efficient cycling by microbes (32).

The culmination of these improvements in soil health and nutrient availability was directly translated into superior plant growth and, ultimately, grain yield (33). The PMH-14 variety consistently demonstrated its superior genetic potential, but it was the synergistic interaction with precision N management that unlocked its full capacity (34). The superior yield of PMH-14 under CCM 50 reflects the synergistic effect of genotype and nutrient management. Timely nitrogen availability supported greater canopy expansion and photosynthetic efficiency, resulting in increased cob girth, grain number and ultimately higher grain yield (35). A larger canopy, facilitated by timely N, captures more solar radiation, driving the production of photosynthates necessary for grain filling. This explains the significant positive impact on all measured yield attributes (36). The combination of PMH-14 and CCM 50 produced the heaviest test weight, largest cob girth and the highest number of grains per cob, culminating in a grain yield (9.26 t/ha) that substantially surpassed all other treatment combinations (37). This interaction highlights a critical principle: the benefits of an improved genotype and an advanced management practice are not merely additive, but multiplicative (38). Conversely, the poor performance of the less responsive ADV-9293 variety, especially when combined with the slower-release organic blend or standard RDF, demonstrates how a mismatch between genetics and management can constrain yield potential (39).

From a practical and economic standpoint, the adoption of CCM-based nitrogen management reduces fertilizer use by up to 25-50 % without compromising yield, while boosting grain production by approximately 20-25 %. This dual benefit makes CCM a cost-effective and attractive option for farmers seeking higher profits with lower input costs (40-43). This study was limited to a single season and location. Longer-term trials across diverse soil types, climatic conditions and maize genotypes are essential to confirm the generalizability of these findings. Additionally, socio-economic factors such as farmer awareness and the cost of sensor tools must be considered before wider adoption (44). Future research should validate these findings across multiple agro-ecologies through multi-location, long-term trials to assess the cumulative impact on soil health and carbon sequestration (45). Incorporating digital decision-support platforms like the Pusa N Doctor app, can enhance wider adoption, while breeding efforts should focus on developing hybrids with high responsiveness to precision nitrogen management (46). In conclusion, this research strongly supports the adoption of sensor-based, real-time nitrogen management as a cornerstone of sustainable maize intensification, offering a pathway to simultaneously achieve high yields, improve soil health and secure greater economic returns for farmers.

Conclusion

Real-time nitrogen management using CCM and LCC significantly improved maize yield, nitrogen use efficiency and soil health in Punjab's Trans-Gangetic Plains. The CCM 50 threshold with PMH-14 was most effective, enhancing soil enzymes, organic carbon and plant growth while reducing fertilizer inputs. Precision nitrogen tools provide a profitable, sustainable strategy for climate-smart maize intensification. Multi-location and long-term trials are required to validate these findings across diverse agro-ecological environments.

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Authors' contributions

AB contributed to the conceptualization, data curation, formal analysis, investigation, methodology, statistical analysis, writing - original draft and writing - review and editing. AP, TT, MK and MBP were involved in data curation, formal analysis, investigation, methodology and writing - original draft. NR contributed to data curation, formal analysis, investigation, methodology, statistical analysis and writing - review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

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