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RESEARCH ARTICLE

Real time nitrogen management using chlorophyll content measurements for improved kharif maize performance

Ayush Baliyan[1*], Amol Pawar[1], Navjot Rana[1*], Swati Mehta[1] & Bheem Pareek[2]

[1]Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144 411, Punjab, India
[2]Department of Agronomy, Rajasthan Agricultural Research Institute, Sri Karan Narendra Agriculture University, Jaipur 302 017, Rajasthan, India

*Correspondence email - baliyanayush98@gmail.com, navjotrana7@gmail.com

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Abstract

Maize production in India's Punjab region is crucial for food security but faces challenges in nitrogen (N) use efficiency. Conventional blanket N applications often lead to environmental losses and reduced profitability. This study investigated the efficacy of real-time precision nitrogen management using a leaf color chart (LCC) and chlorophyll content meter (CCM) on the growth, physiology and yield of three maize hybrids (PMH14, PMH13, ADV9293) in the Punjab central plains during the 2024 kharif season. A split-plot design was employed with hybrids as main plots and six N management strategies as sub-plots: LCC-based N application at thresholds 4 and 5, CCM-based application at thresholds 40 and 50, a combination of 50 % nano-N + 50 % inorganic N and a control of 100 % recommended dose of fertilizer (RDF; 120:30:30 kg/ha N:P:K). Results demonstrated that sensor-guided N management, particularly CCM 50, significantly enhanced key parameters compared to conventional methods. The hybrid PMH14 exhibited superior performance, achieving the highest plant height (130.20 cm), leaf area (4317.59 cm^2), cob length (23.39 cm), total chlorophyll content (42.00 mg/g FW) and grain yield (8.35 t/ha). Critically, the interaction between PMH14 and the CCM 50 treatment yielded the maximum grain output (10.13 t/ha). These findings conclusively show that synchronizing N supply with crop demand through high-threshold sensor-based management optimizes physiological processes, improves nitrogen use efficiency and significantly boosts productivity, offering a sustainable alternative to fixed-schedule N fertilization for maize in similar agro-climatic zones.

Keywords: chlorophyll content meter; leaf color chart; nitrogen use efficiency; real-time nitrogen management

Introduction

Maize (*Zea mays* L.) stands as one of the most significant cereal crops globally, forming the backbone of food, fodder and industrial raw material supply chains (1). In India, maize ranks as the third major cereal after rice and wheat, owing to its versatile adaptation, high productivity and expanding role in poultry feed, starch, ethanol and processed food industries (2). Globally, India occupies the sixth position in maize production, with output crossing 35 million tonnes in 2022-23, over an estimated 9.8 million hectares, trailing behind world leaders like the United States, China, Brazil, Argentina and Ukraine (3). Within India, maize productivity hovers around 3.5 tonnes per hectare, significantly higher than earlier decades, reflecting improved hybrid adoption, agronomic practices and fertilizer management (4). States such as Andhra Pradesh, Karnataka, Maharashtra, Bihar and Punjab are the leading contributors, collectively accounting for over 60 % of the nation's maize production (5). Punjab, although better known for rice and wheat, has witnessed a remarkable shift towards maize cultivation in the last decade, driven by water sustainability concerns, crop diversification schemes and robust hybrid technology (6).

Punjab's central plain region is distinguished by fertile alluvial soils, a sub-tropical monsoon climate and advanced irrigation infrastructure-factors that favor maize, especially during the Kharif season (7). In response to depleting groundwater and fluctuating market incentives for rice, the Government of Punjab has promoted maize as a strategic alternative through the Crop Diversification Programme (CDP), Minimum Support Price (MSP) incentives and improved extension services (8). In 2022-23, Punjab's maize acreage surpassed 155,000 hectares, with an average productivity ranging from 4.2 to 4.8 tonnes per hectare, notably surpassing the national average (9). Districts such as Ludhiana, Kapurthala, Hoshiarpur and parts of the central plain constitute major production belts, with robust hybrid seed adoption (PMH14, PMH13, ADV9293 and others) pushing yield frontiers (6). Maize in Punjab is integral to ensuring livestock feed, silage for dairy and is poised to supplement state foodgrain targets under the National Food Security Act (10).

Despite these gains, maize intensification in Punjab central plain is confronted by agronomic and economic challenges, the most pertinent being the efficient management of macronutrients-especially nitrogen (N) (11). Nitrogen is the principal driver of maize growth, yield and grain protein quality (12). Inadequate or imbalanced N supplementation can restrict leaf area expansion, limit photosynthetic capacity and reduce ear development, ultimately impacting grain yield and profitability (13). Conversely, excessive and ill-timed N application risks leaching, volatilization and nitrous oxide emissions, causing financial losses and aggravating environmental concerns-particularly in Punjab's groundwater-

sensitive agro-ecosystem (14). Traditionally, nitrogen management in Punjab is governed by blanket fertilizer recommendations or split-application schedules based on calendar dates, often leading to mismatch between crop demand and soil supply due to variability in monsoon onset, irrigation adequacy, hybrid responsiveness and within-field soil heterogeneity (15).

Real time nitrogen management offers an innovative solution to the challenge of synchronizing fertilizer use with the needs of the maize crop, particularly in Punjab's central plains, where traditional nitrogen practices often lead to inefficiency and environmental risk (16). Tools like the Leaf Color Chart (LCC), NDVI and SPAD indices now enable farmers to assess nitrogen status directly in the field, adjusting application timing to key growth stages such as V4, V8, tasselling and silking (17). LCC-based strategies, supported by research at Punjab Agricultural University, have demonstrated yield improvements of 8-15 %, plus reductions in fertilizer use and soil nitrate pollution (18). Despite promising results, adoption across the region remains limited, with most benefits seen among progressive farmers (4). Comprehensive monitoring of agronomic and physiological traits in hybrid maize varieties (such as PMH14, PMH13, ADV9293) under Punjab's soil and irrigation conditions will enable the development of real-time nitrogen recommendations that optimize productivity, profitability and environmental sustainability, despite current barriers such as limited extension services and digital tool accessibility.

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: PMH14, PMH13 and ADV9293. Sub-plots received six nitrogen management treatments:

Table 1. Treatment details

S. No.	Treatments	
1	T1	Leaf Color Chart (LCC) 4
2	T2	Leaf Color Chart (LCC) 5
3	T3	Chlorophyll Content Meter (CCM) 40
4	T4	Chlorophyll Content Meter (CCM) 50
5	T5	50 % Nano N + 50 % Inorganic N
6	T6	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, tasselling).

All parameters were measured on representative samples at 60 DAS, as specified, ensuring reliable treatment comparisons and robust statistical analyses.

Parameters and Measurement Methods

Morphological parameters

Plant height (cm): Plant height was recorded from the base of the plant at soil surface to the tip of the longest leaf using a measuring scale. Measurements were made at 60 DAS and expressed in centimetres (cm).

Number of leaves (number/plant): The total number of fully expanded leaves per plant was counted manually at 60 days after sowing and reported as number per plant.

Stem girth (mm): Stem girth was measured at the first internode above soil using a digital vernier caliper and values were recorded in millimetres (mm).

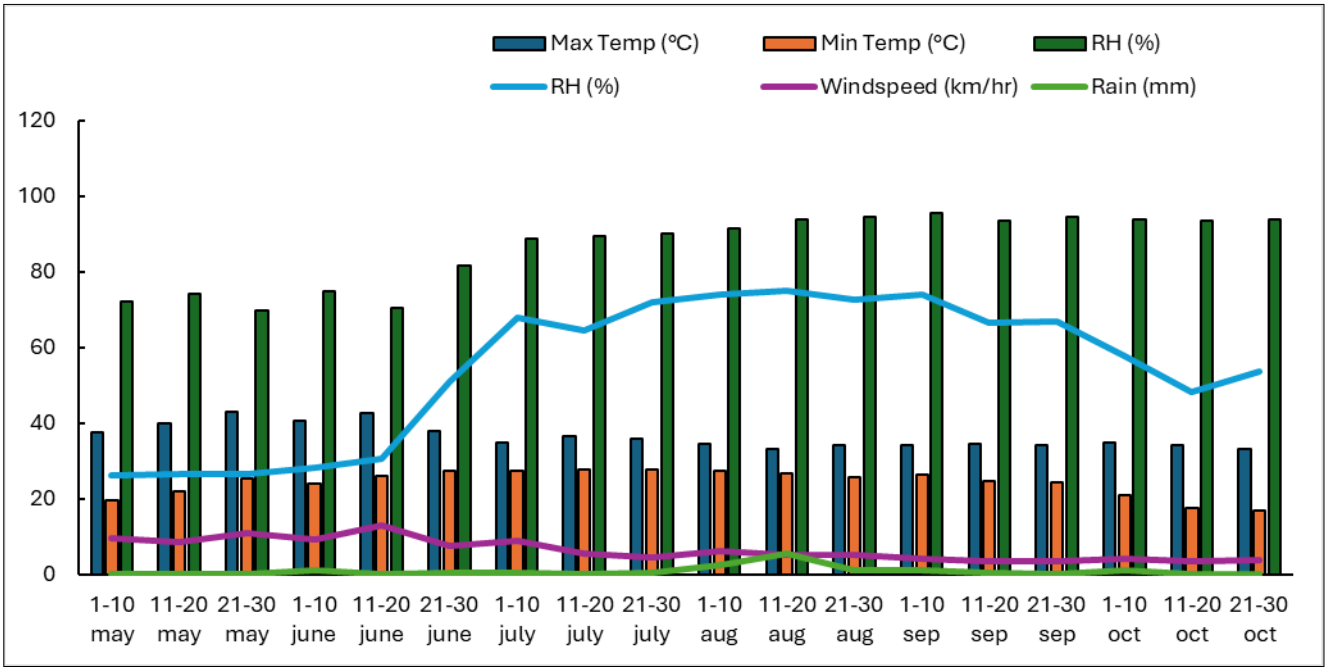

Fig. 1. Standard meteorological week data of weather data 2024.

Leaf length (cm): The length of the characteristic leaf was measured from its base to the tip with a measuring tape and expressed in centimetres (cm).

Leaf area (cm^2): Leaf area was measured using a portable leaf area meter and results were reported in square centimetre (cm^2).

Cob length (cm): Cob length was measured at harvest from the base to the tip of the cob using a ruler, expressed in centimetre (cm).

Physiological parameters

Leaf nitrogen content (%): Leaf nitrogen content was measured by the Kjeldahl digestion technique, with values calculated as percentage (%) of dry leaf mass (19).

Total chlorophyll content (mg/g FW): Chlorophyll content was estimated using a non-maceration method with dimethyl sulfoxide (DMSO) as the solvent (20). A fresh leaf sample weighing 0.05 g was incubated in 10 mL of DMSO in darkness for 24 hours or until the tissue became colourless. The absorbance of the resulting extract was then measured at 645 nm and 663 nm using a spectrophotometer, with a DMSO blank for calibration.

Total chlorophyll concentration was calculated using the following formula (21) and expressed in mg/g fresh weight (FW):

Total Chlorophyll (mg/g FW) = (20.2×A645) + (8.02×A663) (20.2×A645) + (8.02×A663) × (V / W) (Eqn. 1)

Membrane Stability Index (MSI, %): This parameter was determined at 45 and 55 DAT using 100 mg of 2 cm leaf discs from the third fully developed leaf (20). Discs were placed in two sets of test tubes containing 10 mL double-distilled water. One set was incubated at 40 °C for 30 min to measure initial electrical conductivity (C1) and the other at 100 °C for 10 min to measure final conductivity (C2). MSI was calculated as:

$$MSI\ \% = [1 - \left(\frac{C1}{C2}\right) x\ 100 \quad \text{(Eqn. 2)}$$

Biochemical parameters

Protein content (%): Protein content was estimated using the Kjeldahl method (AOAC, 1990), wherein the total nitrogen content was determined and converted to protein by multiplying by a factor of 6.25. The data were expressed as a percentage (%) on a dry weight basis (22).

Sucrose, glucose and fructose (mg/g dry tissue): Soluble sugars were extracted from dried plant tissue with ethanol and quantified calorimetrically or by high-performance liquid chromatography (HPLC) following the method of Dubois et al. (1956). Results were expressed as milligrams per gram (mg/g) of dry tissue (23).

Yield attribute

Grain yield (t ha^{-1}): Grain yield was calculated after harvesting, drying and threshing from each plot, adjusted to a 12 % moisture basis and then expressed as tonnes per hectare (t ha^{-1}).

Nutrient content parameters

Nitrogen content (kg ha^{-1}): Nitrogen concentration in plant tissue was determined by the Kjeldahl method after acid digestion and calculated as kilograms per hectare (kg ha^{-1}) (19).

Phosphorus content (kg ha^{-1}): Phosphorus content was estimated calorimetrically using the vanado-molybdate method following acid digestion and expressed as kilograms per hectare (kg ha^{-1}) (24).

Potassium content (kg ha^{-1}): Potassium was determined by flame photometry in acid-digested samples and results expressed in kilograms per hectare (kg ha^{-1}) (25).

Results and Discussion

Morphological parameters

Plant height

At 60 days after sowing, plant height showed significant differences among main and sub-plot treatments (Table 2). Among hybrids, PMH14 recorded the maximum height (130.20 cm), significantly higher than PMH13 (114.21 cm) and ADV9293 (87.65 cm), while PMH13 showed intermediate performance. The minimum height in ADV9293 indicated genotypic variation in growth response. Among nitrogen management practices, CCM 50 produced the tallest plants (118.49 cm), followed by LCC 5 (115.02 cm), CCM 40 (113.72 cm) and LCC 4 (111.39 cm). Conventional fertilization treatments showed lower values, with 100% RDF (104.42 cm) and 50 % organic + 50 % inorganic (101.09 cm) recording the least growth. The main × sub interaction was non-significant, indicating uniform response of nitrogen treatments across hybrids.

Table 2. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on plant height (cm) at different growth stages

Plant height (cm)	
Main plot	
Treatments	60 DAS
PMH14	130.20
PMH13	114.21
ADV9293	87.65
SE (m) ±	0.44
LSD at 5 %	1.73
Sub-plot	
(LCC) 4	111.39
(LCC) 5	115.02
(CCM) 40	113.72
(CCM) 50	118.49
50 % (Organic) + 50 % (Inorganic)	101.09
100 % (RDF)	104.42
SE (m) ±	0.34
LSD at 5 %	0.99
Main Sub (Interaction)	
SE (m) ±	0.59
LSD at 5 %	NS

The significant variation in plant height among hybrids and nitrogen management practices highlights the influence of genetic potential and nutrient supply strategies on maize growth. PMH14 outperformed the other hybrids, reflecting its superior vigor and adaptability under the given conditions (26). The enhanced growth under CCM and LCC-based treatments, particularly CCM 50, suggests that sensor-guided nitrogen application effectively met the crop's nitrogen demand during the early growth phase (17). In contrast, conventional and partially organic treatments resulted in shorter plants, indicating suboptimal nutrient availability (27). The non-significant interaction between hybrids and nitrogen treatments suggests that all hybrids responded similarly to the nitrogen management strategies, confirming the consistency of treatment effects across genotypes (28).

Number of leaves

At 60 days after sowing, the number of leaves per plant showed significant differences among main and sub-plot treatments (Table 3). PMH14 recorded the highest leaf count (13.55), significantly higher than PMH13 (11.04) and ADV9293 (10.02), the lowest. Among nitrogen management practices, CCM 50 showed the maximum number of leaves (12.32), followed by LCC 5 (12.02), CCM 40 (11.66) and LCC 4 (11.50). Conventional treatments like 100 % RDF (10.87) and 50 % organic + 50 % inorganic (10.53) recorded lower values.

Table 3. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on no. of leaves at different growth stages

No of leaves	
Main plot	
Treatments	60 DAS
PMH14	13.55
PMH13	11.04
ADV9293	10.02
SE (m) ±	0.07
LSD at 5 %	0.29
Sub-plot	
(LCC) 4	11.50
(LCC) 5	12.02
(CCM) 40	11.66
(CCM) 50	12.32
50 % (Organic) + 50 % (Inorganic)	10.53
100 % (RDF)	11.17
SE (m) ±	0.06
LSD at 5 %	0.16
Main Sub (Interaction)	
SE (m) ±	0.10
LSD at 5 %	NS

The interaction effect between main and sub-plot treatments on leaf number was non-significant (NS).

Significant variation in leaf number among hybrids reflected genetic differences in vegetative growth, with PMH14 showing superior canopy development and better nitrogen use efficiency (29). Lower leaf counts in ADV9293 indicated limited growth potential (30). Sensor-based nitrogen management (CCM 50 and LCC 5) enhanced leaf production through timely nitrogen supply, whereas conventional and organic treatments showed fewer leaves due to reduced nutrient availability (17). The non-significant interaction revealed a consistent response of all hybrids to nitrogen management practices (17).

Stem girth

At 60 DAS, stem girth showed no significant differences among main and sub-plot treatments (Table 4). Among hybrids, PMH14 recorded the highest stem girth (38.06 mm), followed by PMH13 (35.47 mm) and ADV9293 (33.06 mm), though the variation was statistically non-significant (LSD = 2.04 mm). Across nitrogen management practices, CCM 50 registered the highest value (36.66 mm), followed by LCC 5 (36.10 mm), CCM 40 (35.71 mm) and the lowest in 50 % organic + 50 % inorganic treatment (34.48 mm).

The main × sub interaction effect on stem girth was non-significant, indicating a consistent response to nitrogen management across all maize hybrids.

The non-significant variation in stem girth among hybrids and nitrogen management treatments suggests similar vegetative growth under the prevailing conditions (31). Although PMH14 showed a numerically higher stem girth, the differences were statistically negligible (32). Likewise, slightly higher values under CCM 50 and LCC 5 indicated a positive but non-significant influence of sensor-based nitrogen management on stem thickness (33). The non-significant interaction confirmed that all maize hybrids exhibited a uniform response to different nitrogen management approaches (34).

Table 4. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on stem girth(mm) at different growth stages

Steam girth	
Main plot	
Treatments	60 DAS
PMH14	38.06
PMH13	35.47
ADV9293	33.06
SE (m) ±	2.04
LSD at 5 %	NS
Sub-plot	
(LCC) 4	35.30
(LCC) 5	36.10
(CCM) 40	35.71
(CCM) 50	36.66
50 % (Organic) + 50 % (Inorganic)	34.48
100% (RDF)	34.92
SE (m) ±	3.38
LSD at 5 %	NS
Main Sub (Interaction)	
SE (m) ±	5.85
LSD at 5 %	NS

Leaf length

At 60 DAS, leaf length varied significantly among main plot treatments (Table 5). PMH14 recorded the highest leaf length (68.07 cm), followed by PMH13 (65.30 cm) and ADV9293 (55.63 cm), showing the effect of genetic variation on leaf elongation. Sub-plot treatments of nitrogen management showed non-significant differences, with CCM 50 recording the highest leaf length (66.27 cm) and 50 % organic + 50 % inorganic treatment the lowest (60.26 cm). The main × sub interaction effect on leaf length was non-significant.

Table 5. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on leaf length at different growth stages

Leaf length	
Main plot	
Treatments	60 DAS
PMH14	68.07
PMH13	65.30
ADV9293	55.63
SE (m) ±	1.57
LSD at 5 %	6.16
Sub-plot	
(LCC) 4	61.94
(LCC) 5	65.13
(CCM) 40	63.04
(CCM) 50	66.27
50 % (Organic) + 50 % (Inorganic)	60.26
100 % (RDF)	61.35
SE (m) ±	2.43
LSD at 5%	NS
Main Sub (Interaction)	
SE (m) ±	4.20
LSD at 5 %	NS

The significant variation in leaf length among maize hybrids reflects genetic differences influencing leaf elongation potential (35). The superior leaf length of PMH14 indicates its greater vegetative vigor and efficient utilization of available resources compared to PMH13 and ADV9293(40). The absence of significant differences among nitrogen management treatments suggests that all approaches met the crop's nitrogen requirement adequately at this stage (36). Slightly higher values under CCM 50 and lower under 50 % organic + 50 % inorganic treatments indicate that sensor-based nitrogen management may support better leaf expansion, though not to a statistically significant extent (37). The non-significant interaction further implies a uniform response of hybrids to different nitrogen management strategies (38).

Leaf area

Leaf area at 60 days after sowing (DAS) displayed significant differences among the main plot treatments (Table 6). PMH14 had the highest leaf area (4317.59 cm^2), followed closely by PMH13 (4295.64 cm^2), while ADV9293 recorded the lowest leaf area (4273.09 cm This response highlights the influence of genotypic differences on leaf area development in maize at the studied growth stage. For sub-plot treatments, analysis did not reveal significant differences among the various nitrogen management methods. While CCM 50 recorded the highest leaf area (4304.74 cm^2) and 50 % organic + 50 % inorganic treatment the lowest (4286.53 cm^2), these differences were not statistically meaningful.

Table 6. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on leaf area at different growth stages

Leaf area	
Main plot	
Treatments	60 DAS
PMH14	4317.59
PMH13	4295.64
ADV9293	4273.09
SE (m) ±	3.41
LSD at 5%	13.39
Sub-plot	
(LCC) 4	4293.27
(LCC) 5	4301.12
(CCM) 40	4296.80
(CCM) 50	4304.74
50% (Organic) + 50% (Inorganic)	4286.53
100% (RDF)	4290.16
SE (m) ±	5.04
LSD at 5%	NS
Main Sub (Interaction)	
SE (m) ±	8.72
LSD at 5%	NS

The main × sub interaction was also non-significant (NS), indicating that the effect of nitrogen management on leaf area was consistent regardless of the hybrid.

The significant variation in leaf area among maize hybrids emphasizes the role of genetic factors in determining canopy development (39). The higher leaf area observed in PMH14 and PMH13 suggests their superior vegetative growth potential and efficient photosynthetic surface development compared to ADV9293 (40). The absence of significant differences among nitrogen management treatments indicates that all approaches provided sufficient nitrogen to support leaf area expansion (41). Slightly higher values under CCM 50 reflect the potential advantage of sensor-based nitrogen application in maintaining optimal nitrogen status, though the differences were not significant (42). The non-significant interaction further confirms that nitrogen management had a uniform effect on all hybrids (43)

Length of cob

Cob length recorded at 60 days after sowing (DAS) showed significant differences among the main plot treatments (Table 7). The highest cob length was observed in PMH14 (23.39 cm), followed by PMH13 (20.63 cm), while the lowest cob length was recorded in ADV9293 (16.50 cm). In the sub-plot treatments, which encompassed various nitrogen management strategies, significant variation was also observed for cob length. The CCM 50 treatment resulted in the maximum cob length (22.05 cm), closely followed by LCC 5 (21.23 cm), while the 50 % organic + 50 % inorganic treatment exhibited the lowest cob length (18.25 cm).

Table 7. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on length of cob at different growth stages

Length of cob	
Main plot	
Treatments	60 DAS
PMH14	23.39
PMH13	20.63
ADV9293	16.50
SE (m) ±	0.11
LSD at 5%	0.44
Sub-plot	
(LCC) 4	19.82
(LCC) 5	21.23
(CCM) 40	20.52
(CCM) 50	22.05
50 % (Organic) + 50 % (Inorganic)	18.25
100% (RDF)	19.16
SE (m) ±	0.15
LSD at 5 %	0.44
Main Sub (Interaction)	
SE (m) ±	0.26
LSD at 5 %	NS

The interaction between main plot and sub-plot treatments was found to be non-significant, indicating that the effect of different nitrogen management practices on cob length did not vary with hybrid.

Significant variation in cob length among maize hybrids reflects the influence of genetic potential on reproductive growth (44). The highest cob length in PMH14 indicates its superior sink development and better translocation of assimilates, while shorter cobs in ADV9293 suggest limited growth vigor (45). Significant differences among nitrogen management treatments show the positive impact of precise nitrogen application on cob elongation (11). The greater cob length under CCM 50 and LCC 5 treatments demonstrates the advantage of sensor-based nitrogen management in meeting crop nitrogen demand efficiently (14). The non-significant interaction implies that all hybrids responded similarly to nitrogen management strategies in terms of cob development (12).

Physiological parameters

Leaf nitrogen content

At 60 DAS, leaf nitrogen content showed significant variation among both maize hybrids and nitrogen management practices (Table 8). Among hybrids, PMH14 recorded the highest nitrogen content (200.19), followed by PMH13 (196.69) and ADV9293 (190.99), indicating the effect of genotypic variation on nitrogen accumulation. Among nitrogen management practices, CCM 50 showed the highest value (198.37), followed by LCC 5 (198.03), while the lowest was observed in the 50 % organic + 50 % inorganic treatment (192.31).

Table 8. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on leaf nitrogen content at different growth stages

Leaf nitrogen content	
Main plot	
Treatments	60 DAS
PMH14	3.24
PMH13	2.68
ADV9293	2.10
SE (m) ±	0.00
LSD at 5 %	0.02
Sub-plot	
(LCC) 4	2.63
(LCC) 5	2.87
(CCM) 40	2.73
(CCM) 50	2.89
50 % (Organic) + 50 % (Inorganic)	2.43
100 % (RDF)	2.49
SE (m) ±	0.02
LSD at 5 %	0.07
Main Sub (Interaction)	
SE (m) ±	0.04
LSD at 5 %	0.12

The main × sub interaction was significant, with the combination of PMH14 and CCM 50 recording the highest nitrogen content (202.55) and ADV9293 with 50% organic + 50% inorganic showing the lowest (183.51) (Table 9).

The significant variation in leaf nitrogen content among hybrids and nitrogen management practices highlights the influence of genetic and management factors on nitrogen uptake and assimilation in maize (31). The higher nitrogen content in PMH14 reflects its superior nutrient uptake efficiency and stronger physiological capacity to accumulate nitrogen compared to PMH13 and ADV9293(4). Among nitrogen management practices, the higher nitrogen content under CCM 50 and LCC 5 indicates that real-time, sensor-based nitrogen application effectively maintained adequate nitrogen levels in plant tissue (17). In contrast, the lower value under 50 % organic + 50 % inorganic treatment suggests limited nitrogen availability from partial organic sources (31). The significant interaction between hybrids and nitrogen management implies that the effect of nitrogen application varied with genotype, with the PMH14 × CCM 50 combination performing best due to efficient nitrogen use and synchronization between crop demand and supply (17).

Table 9. Interaction effect of nutrient management practices on nitrogen at 30 days after sowing (das)

(Interaction)60DAS				
	V 1	V 2	V 3	**Mean A**
T 1	3.20	2.60	2.10	**2.63**
T 2	3.50	2.80	2.30	**2.87**
T 3	3.30	2.80	2.10	**2.73**
T 4	3.50	2.87	2.30	**2.89**
T 5	2.90	2.50	1.90	**2.43**
T 6	3.07	2.50	1.90	**2.49**
Mean B	**3.24**	**2.68**	**2.10**	
SE (m) ±		0.04		
LSD at 5%		0.12		

Total chlorophyll content

At 60 DAS, total chlorophyll content differed significantly among maize hybrids and nitrogen management treatments (Table 10). Among hybrids, PMH14 recorded the highest value (42.00), followed by PMH13 (41.14) and ADV9293 (40.29), indicating genetic variation in chlorophyll content. Among nitrogen management practices, CCM 50 (48.77) and LCC 5 (48.38) showed the highest chlorophyll levels, while 100% RDF (37.60) and 50 % organic + 50 % inorganic (35.69) recorded the lowest values.

Table 10. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on total chlorophyl content at different growth stages

Total Chlorophyl content	
Main plot	
Treatments	60 DAS
PMH14	42.00
PMH13	41.14
ADV9293	40.29
SE (m) ±	0.03
LSD at 5 %	0.13
Sub-plot	
(LCC) 4	38.00
(LCC) 5	48.38
(CCM) 40	38.41
(CCM) 50	48.77
50 % (Organic) + 50 % (Inorganic)	35.69
100% (RDF)	37.60
SE (m) ±	0.03
LSD at 5%	0.09
Main Sub (Interaction)	
SE (m) ±	0.05
LSD at 5 %	0.16

The main × sub interaction was significant, with the highest chlorophyll content in PMH14 under CCM 50 (49.51) and the lowest in ADV9293 under 50 % organic + 50 % inorganic (35.09), reflecting the stronger positive impact of precision nitrogen management on the high-yielding hybrid PMH14(Table 11).

The significant variation in total chlorophyll content among hybrids signifies the influence of genetic makeup on chlorophyll synthesis and photosynthetic efficiency (28). The higher chlorophyll content in PMH14 indicates its superior physiological activity and nitrogen assimilation capacity compared to PMH13 and ADV9293 (10). Among nitrogen management practices, the higher chlorophyll levels under CCM 50 and LCC 5 highlight the effectiveness of precision nitrogen management in maintaining optimal nitrogen supply and promoting chlorophyll formation (8). Conversely, lower chlorophyll content in the 100 % RDF and 50 % organic + 50 % inorganic treatments suggest inadequate or imbalanced nitrogen availability (39). The significant interaction between hybrids and nitrogen management shows that PMH14 under CCM 50 responded most favourably, demonstrating a synergistic relationship between genotype potential and real-time nitrogen application (33).

Table 11. Interaction effect of nutrient management practices on nitrogen at 30 days after sowing (das)

(Interaction)60DAS				
	V 1	**V 2**	**V 3**	**Mean A**
T 1	38.73	38.13	37.13	**38.00**
T 2	49.23	48.14	47.78	**48.38**
T 3	39.54	38.47	37.21	**38.41**
T 4	49.51	48.67	48.13	**48.77**
T 5	36.41	35.57	35.09	**35.69**
T 6	38.55	37.83	36.41	**37.60**
Mean B	**42.00**	**41.14**	**40.29**	
SE (m) ±		0.05		
LSD at 5 %		0.16		

MSI

MSI (membrane stability index) evaluated at 60 days after sowing (DAS) revealed significant differences among the main plot treatments (Table 12). The highest MSI value was recorded in PMH14 (82.09), with PMH13 (78.33) and ADV9293 (74.66) showing comparatively lower stability indices. However, analysis of sub-plot treatments based on nitrogen management strategies did not show significant differences, as the LSD value was non-significant (NS). The greatest MSI was seen in CCM 50 (80.12) and the lowest in the 50 % organic + 50 % inorganic regime (76.73), but these differences lacked statistical confirmation.

Table 12. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on msi at different growth stages

MSI	
Main plot	
Treatments	60 DAS
PMH14	82.09
PMH13	78.33
ADV9293	74.66
SE (m) ±	0.68
LSD at 5 %	2.68
Sub-plot	
(LCC) 4	78.09
(LCC) 5	79.17
(CCM) 40	78.69
(CCM) 50	80.12
50 % (Organic) + 50 % (Inorganic)	76.73
100% (RDF)	77.36
SE (m) ±	1.43
LSD at 5 %	NS
Main Sub (Interaction)	
SE (m) ±	2.47
LSD at 5 %	NS

Similarly, the main × sub interaction was non-significant, indicating that genotypic response to nitrogen management strategies with respect to MSI was uniform across all treatments.

The significant variation in MSI among maize hybrids reflects the genetic influence on cellular integrity and physiological tolerance under field conditions (11). The higher MSI value in PMH14 suggests greater membrane stability and efficient physiological functioning, while lower values in PMH13 and ADV9293 indicate relatively weaker stress resistance (29). The non-significant variation among nitrogen management treatments implies that all nitrogen strategies maintained comparable membrane stability levels at this growth stage (17). Slightly higher MSI under CCM 50 indicates the potential advantage of precise nitrogen application in sustaining membrane integrity, though the response was statistically similar across treatments (31). The non-significant interaction further confirms that hybrids responded uniformly to nitrogen management in terms of membrane stability (36).

Biochemical parameters

Protein

At 60 DAS, protein content showed no significant differences among main or sub-plot treatments (Table 13). Among hybrids, PMH14 recorded the highest protein content (9.88 %), followed by PMH13 (9.33 %) and ADV9293 (8.85 %), indicating that genotypic variation had little influence on protein accumulation. Across nitrogen management practices, CCM 50 showed the highest value (9.58 %), while the 50 % organic + 50 % inorganic treatment recorded the lowest (8.98 %), though differences were non-significant.

Table 13. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on protein at different growth stages

Protein	
Main plot	
Treatments	60 DAS
PMH14	9.88
PMH13	9.33
ADV9293	8.85
SE (m) ±	0.24
LSD at 5%	NS
Sub-plot	
(LCC) 4	9.39
(LCC) 5	9.50
(CCM) 40	9.44
(CCM) 50	9.58
50 % (Organic) + 50 % (Inorganic)	8.98
100 % (RDF)	9.24
SE (m) ±	0.29
LSD at 5 %	NS
Main Sub (Interaction)	
SE (m) ±	0.50
LSD at 5 %	NS

The main × sub interaction was also non-significant, suggesting that protein content remained stable across all genotype and nitrogen management combinations.

The non-significant variation in protein content among maize hybrids and nitrogen management treatments indicates that protein synthesis remained relatively stable under the given conditions (34). Although PMH14 recorded slightly higher values, the differences were not substantial enough to suggest a strong genotypic effect on protein accumulation (18). Similarly, nitrogen management strategies did not significantly alter protein content, implying that all treatments supplied sufficient nitrogen to meet the crop's metabolic needs (15). The marginally higher protein under CCM 50 suggests that sensor-based nitrogen application maintained balanced nitrogen availability, but the effect was statistically comparable with other treatments (35). The non-significant interaction confirms that both genotype and nitrogen management exerted uniform influence on protein formation (7).

Sucrose of plant

At 60 DAS, sucrose content showed significant differences among both main and sub-plot treatments (Table 14). Among hybrids, PMH14 recorded the highest sucrose concentration (28.58), followed by PMH13 (25.62) and ADV9293 (22.06). Across nitrogen management practices, CCM 50 showed the highest sucrose content (26.59), closely followed by LCC 5 (26.11), while the 50% organic + 50% inorganic treatment recorded the lowest (24.50).

Table 14. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on sucrose of plant at different growth stages

Sucrose of plant	
Main plot	
Treatments	60 DAS
PMH14	28.58
PMH13	25.62
ADV9293	22.06
SE (m) ±	0.06
LSD at 5 %	0.23
Sub-plot	
(LCC) 4	25.12
(LCC) 5	26.11
(CCM) 40	25.48
(CCM) 50	26.59
50 % (Organic) + 50 % (Inorganic)	24.50
100 % (RDF)	24.73
SE (m) ±	0.05
LSD at 5 %	0.16
Main Sub (Interaction)	
SE (m) ±	0.09
LSD at 5 %	NS

The main × sub interaction was non-significant, indicating that sucrose accumulation was influenced independently by genotype and nitrogen management without interactive effects.

The significant variation in sucrose content among maize hybrids indicates the effect of genetic factors on carbohydrate metabolism and assimilate accumulation (34). The higher sucrose level in PMH14 suggests greater photosynthetic efficiency and better translocation of assimilates compared to PMH13 and ADV9293(41). Among nitrogen management practices, the higher sucrose content under CCM 50 and LCC 5 reflects the advantage of sensor-based nitrogen application in supporting efficient carbon assimilation and sugar synthesis through balanced nitrogen availability (26). The lower sucrose concentration in the 50 % organic + 50 % inorganic treatment may be due to limited nitrogen release and reduced metabolic activity (5). The non-significant interaction between hybrids and nitrogen management indicates that all genotypes responded similarly to different nitrogen strategies with respect to sucrose accumulation (2).

Glucose

At 60 DAS, glucose content showed significant differences among both main and sub-plot treatments (Table 15). Among hybrids, PMH14 recorded the highest glucose content (17.37), followed by PMH13 (14.29) and ADV9293 (12.33), indicating genotypic variation in glucose accumulation and metabolic efficiency. Across nitrogen management practices, CCM 50 recorded the highest glucose content (16.36), followed by LCC 5 (15.08), CCM 40 (14.73), LCC 4 (14.10), 100 % RDF (13.98) and the lowest in 50 % organic + 50 % inorganic treatment (13.72), showing the superiority of precision nitrogen management at higher thresholds in enhancing glucose accumulation.

Table 15. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on glucose of plant at different growth stages

Glucose of plant	
Main plot	
Treatments	60 DAS
PMH14	17.37
PMH13	14.29
ADV9293	12.33
SE (m) ±	0.04
LSD at 5 %	0.16
Sub-plot	
(LCC) 4	14.10
(LCC) 5	15.08
(CCM) 40	14.73
(CCM) 50	16.36
50 % (Organic) + 50 % (Inorganic)	13.72
100 % (RDF)	13.98
SE (m) ±	0.04
LSD at 5 %	0.11
Main Sub (Interaction)	
SE (m) ±	0.07
LSD at 5 %	0.20

The main × sub interaction was significant, with the highest glucose content in the PMH14 × CCM 50 combination (19.83) and the lowest in the ADV9293 × 50 % organic + 50 % inorganic combination (11.40) (Table 16).

Table 16. Interaction effect of nutrient management practices on nitrogen at 30 days after sowing (das)

(Interaction)60DAS				
	V 1	V 2	V 3	**Mean A**
T 1	16.37	14.03	11.90	**14.10**
T 2	17.90	14.23	13.10	**15.08**
T 3	17.60	14.10	12.50	**14.73**
T 4	19.83	15.97	13.27	**16.36**
T 5	16.20	13.57	11.40	**13.72**
T 6	16.30	13.83	11.80	**13.98**
Mean B	**17.37**	**14.29**	**12.33**	
SE (m) ±		0.07		
LSD at 5%		0.20		

The significant differences in glucose content among maize hybrids highlight the influence of genetic factors on carbohydrate metabolism and sugar synthesis (29). The higher glucose accumulation in PMH14 indicates its greater photosynthetic activity and efficient carbon assimilation compared to PMH13 and ADV9293 (17). Among nitrogen management practices, the higher glucose levels under CCM 50 and LCC 5 reflect the effectiveness of sensor-based nitrogen application in supporting continuous carbon fixation and energy utilization within leaves (32). In contrast, lower glucose content under conventional and organic-integrated treatments suggests limited nitrogen availability and reduced metabolic activity (17). The significant interaction between hybrids and nitrogen management shows that the response of glucose accumulation varied with genotype, with the PMH14 × CCM 50 combination performing best, demonstrating a strong synergy between genetic potential and precision nitrogen management (44).

Fructose

The analysis of fructose content at 60 days after sowing (DAS) revealed significant differences among the main plot treatments (Table 17). Among the three maize hybrids tested, PMH14 recorded the highest fructose content (13.99), followed by PMH13 (12.19), while ADV9293 showed the lowest fructose content (10.39). This demonstrates clear genotypic variation in fructose accumulation among the tested hybrids, with PMH14 exhibiting superior sugar metabolism and carbohydrate partitioning. For the sub-plot treatments representing different nitrogen management strategies, significant differences were also observed in fructose content. The highest fructose content was achieved under the CCM 50 treatment (13.03), followed by LCC 5 (12.83), CCM 40 (12.20) and LCC 4 (12.04). The conventional fertilization approaches showed comparatively lower performance, with 100 % RDF recording 11.63 and the 50 % organic + 50 % inorganic combination exhibiting the lowest fructose content (11.41). This pattern indicates that precision nitrogen management tools, particularly CCM 50 and LCC 5, enhance fructose accumulation in maize plants compared to conventional fertilization methods.

Table 17. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on fructose of plant at different growth stages

Fructose of plant	
Main plot	
Treatments	60 DAS
PMH14	13.99
PMH13	12.19
ADV9293	10.39
SE (m) ±	0.13
LSD at 5 %	0.51
Sub-plot	
(LCC) 4	12.04
(LCC) 5	12.83
(CCM) 40	12.20
(CCM) 50	13.03
50 % (Organic) + 50 % (Inorganic)	11.41
100 % (RDF)	11.63
SE (m) ±	0.15
LSD at 5 %	0.43
Main Sub (Interaction)	
SE (m) ±	0.26
LSD at 5 %	NS

The main × sub interaction was non-significant (NS),

The significant variation in fructose content among maize hybrids highlights the genetic control of sugar metabolism and carbohydrate partitioning (2). The higher fructose level in PMH14 signifies its greater capacity for assimilate conversion and metabolic efficiency compared to PMH13 and ADV9293(37). Among nitrogen management strategies, the higher fructose accumulation under CCM 50 and LCC 5 suggests that sensor-based nitrogen application supports active carbohydrate metabolism by ensuring steady nitrogen supply during growth (36). In contrast, lower values under 100 % RDF and the 50 % organic + 50 % inorganic treatment imply reduced nitrogen availability, which may have limited sugar synthesis (4). The non-significant interaction between hybrids and nitrogen management indicates that all genotypes exhibited a similar pattern of response in fructose accumulation under different nitrogen regimes (17).

Yield attribute

Grain yield

Grain yield at 60 days after sowing differed significantly among hybrids in the main plot, with PMH14 recording the highest yield of 8.35 T/ha, followed by PMH13 (7.06 T/ha), while ADV9293 produced the lowest yield of 6.40 T/ha. Among sub-plot nitrogen management practices, yield differences were also significant, with the highest yield under CCM 50 (8.05 T/ha) and the lowest under 50 % organic + 50 % inorganic (6.80 T/ha), indicating the advantage of precision, sensor-guided N application over conventional or partially organic regimes (Table 18).

Table 18. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on grain yield at different growth stages

Grain yield (T/H)	
Main plot	
Treatments	60 DAS
PMH14	8.35
PMH13	7.06
ADV9293	6.40
SE (m) ±	0.08
LSD at 5 %	0.33
Sub-plot	
(LCC) 4	7.22
(LCC) 5	7.42
(CCM) 40	7.29
(CCM) 50	8.05
50 % (Organic) + 50 % (Inorganic)	6.80
100 % (RDF)	6.86
SE (m) ±	0.08
LSD at 5 %	0.23
Main Sub (Interaction)	
SE (m) ±	0.14
LSD at 5 %	0.40

The main × sub interaction was significant, with the PMH14 × CCM 50 combination achieving the maximum yield of 10.13 T/ha and the ADV9293 × 50 % organic + 50 % inorganic combination the minimum at 5.86 T/ha, demonstrating that yield gains from precise N management were most pronounced in the superior hybrid background (Table 19).

The significant variation in grain yield among maize hybrids and nitrogen management treatments emphasizes the combined influence of genetic potential and nutrient management efficiency on productivity (6). The highest yield in PMH14 reflects its superior growth vigor, better resource utilization and stronger sink development compared to PMH13 and ADV9293(26). Among nitrogen management strategies, the superior yield under CCM 50 and LCC 5 demonstrates the efficiency of sensor-guided nitrogen application in synchronizing nitrogen supply with crop demand, thereby enhancing yield formation (33). Conversely, lower yields under 50 % organic + 50 % inorganic treatment suggest suboptimal nitrogen availability and reduced nutrient uptake efficiency (35). The significant interaction between hybrids and nitrogen management indicates that yield response varied by genotype, with PMH14 under CCM 50 showing the greatest benefit from precision nitrogen management due to its higher genetic yield potential and better nitrogen use efficiency (40).

Table 19. Interaction effect of nutrient management practices on nitrogen at 30 days after sowing (das)

(Interaction)60DAS				
	V 1	**V 2**	**V 3**	**Mean A**
T 1	8.06	7.03	6.58	**7.22**
T 2	8.29	7.23	6.73	**7.42**
T 3	8.15	7.13	6.58	**7.29**
T 4	10.13	7.25	6.76	**8.05**
T 5	7.72	6.81	5.86	**6.80**
T 6	7.75	6.92	5.91	**6.86**
Mean B	**8.35**	**7.06**	**6.40**	
SE (m) ±		0.14		
LSD at 5 %		0.40		

Nutrient content in leaves

Nitrogen

Nitrogen content at 60 days after sowing (DAS) differed significantly among hybrids in the main plot, with PMH14 registering the highest value (200.19), followed by PMH13 (196.69), while ADV9293 recorded the lowest (190.99).Among sub-plot nitrogen management practices, differences were also significant with the highest nitrogen content under CCM 50 (198.37), closely followed by LCC 5 (198.03) and CCM 40 (197.59), whereas the lowest value was observed under the 50 % organic + 50 % inorganic regime (192.31) and 100 % RDF remained intermediate (194.36)(Table 20).

Table 20. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on nitrogen at different growth stages

Nitrogen	
Main plot	
Treatments	60 DAS
PMH14	200.19
PMH13	196.69
ADV9293	190.99
SE (m) ±	1.35
LSD at 5 %	5.32
Sub-plot	
(LCC) 4	195.08
(LCC) 5	198.03
(CCM) 40	197.59
(CCM) 50	198.37
50 % (Organic) + 50 % (Inorganic)	192.31
100% (RDF)	194.36
SE (m) ±	0.86
LSD at 5 %	2.49
Main Sub (Interaction)	
SE (m) ±	1.49
LSD at 5 %	4.32

The interaction between hybrids and nitrogen management was significant, with the maximum nitrogen content in the PMH14 × CCM 50 combination (202.55) and the minimum in the ADV9293 × 50 % organic + 50 % inorganic combination (183.51), demonstrating that precise, sensor-guided nitrogen management particularly amplifies nitrogen accumulation in the superior hybrid background (Table 21).

The significant variation in nitrogen content among maize hybrids indicates the influence of genetic potential on nitrogen uptake and assimilation efficiency (9). The higher nitrogen content in PMH14 reflects its superior nutrient absorption and utilization capacity compared to PMH13 and ADV9293(11). Among nitrogen management practices, the elevated nitrogen levels under CCM 50

Table 21. Interaction effect of nutrient management practices on nitrogen at 30 days after sowing (das)

(Interaction)60DAS				
	V 1	**V 2**	**V 3**	**Mean**
T1	199.59	196.53	189.13	**195.08**
T 2	201.88	197.15	195.06	**198.03**
T 3	200.88	196.96	194.93	**197.59**
T 4	202.55	197.35	195.22	**198.37**
T 5	197.48	195.94	183.51	**192.31**
T 6	198.78	196.21	188.10	**194.36**
Mean	**200.19**	**196.69**	**190.99**	
SE (m) ±		1.49		
LSD at 5 %		4.32		

and LCC 5 treatments highlight the effectiveness of sensor-based nitrogen application in maintaining optimal plant nitrogen status through real-time monitoring and precise nutrient supply (16). In contrast, lower nitrogen content under 50 % organic + 50 % inorganic treatment suggests inadequate nitrogen availability and slower nutrient release (18). The significant hybrid × nitrogen management interaction further demonstrates that the response to nitrogen application varied with genotype, with the PMH14 × CCM 50 combination achieving maximum nitrogen accumulation due to the hybrid's high nitrogen use efficiency and strong physiological vigor under precision nitrogen management (17).

Phosphorus

Phosphorus content at 60 days after sowing (DAS) showed no significant differences among the main plot treatments. Although the mean phosphorus values varied slightly-PMH14 (24.40), ADV9293 (24.24) and PMH13 (24.12)-these differences were statistically non-significant. Similarly, analysis of the sub-plot treatments, representing various nitrogen management regimes, revealed no significant differences in phosphorus content. The highest phosphorus content was observed under CCM 50 (25.09), while the lowest was under LCC 4 (23.59) (Table 22). However, these values did not differ statistically.

Table 22. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on phosphorus at different growth stages

Phosphorus	
Main plot	
Treatments	60 DAS
PMH14	24.40
PMH13	24.12
ADV9293	24.24
SE (m) ±	0.19
LSD at 5 %	NS
Sub-plot	
(LCC) 4	23.59
(LCC) 5	24.14
(CCM) 40	24.38
(CCM) 50	25.09
50 % (Organic) + 50 % (Inorganic)	24.02
100% (RDF)	24.28
SE (m) ±	0.36
LSD at 5 %	NS
Main Sub (Interaction)	
SE (m) ±	0.62
LSD at 5 %	NS

The main × sub interaction was also non-significant (NS), indicating that nitrogen management practices did not interact with genotype to affect phosphorus uptake.

The non-significant variation in phosphorus content among hybrids indicates that genotypic differences had little influence on phosphorus uptake under the given soil and environmental conditions (42). Minor numerical variations, with slightly higher values in PMH14, suggest comparable phosphorus absorption efficiency across hybrids. Similarly, the absence of significant differences among nitrogen management treatments implies that phosphorus availability and uptake were not markedly influenced by nitrogen application methods (45). The marginally higher phosphorus content under CCM 50 may indicate improved root activity and nutrient mobilization under precision nitrogen management, though not statistically distinct (41). The non-significant interaction further confirms that all maize hybrids responded uniformly to nitrogen management practices concerning phosphorus accumulation (4).

Potassium

The results for potassium content at 60 days after sowing (DAS) showed significant differences among the main plot treatments. PMH14 had the highest potassium content (183.10), followed by PMH13 (181.16), while ADV9293 showed the lowest value (178.33), indicating a clear genotypic variation in potassium accumulation among the maize hybrids tested. Among the sub-plot treatments representing different nitrogen management strategies, no significant differences in potassium content were -observed. The highest potassium content was recorded under the CCM 50 treatment (181.55), followed by LCC 5 (181.30), CCM 40 (181.16) and LCC 4 (180.59), while the lowest was observed in the 50 % organic + 50 % inorganic treatment (180.17). However, these differences were not statistically meaningful (Table 23).

Table 23. Effect of leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management on potassium at different growth stages

	Potassium
Main plot	
Treatments	60 DAS
PMH14	183.10
PMH13	181.16
ADV9293	178.33
SE (m) ±	0.56
LSD at 5 %	2.18
Sub-plot	
(LCC) 4	180.59
(LCC) 5	181.30
(CCM) 40	181.16
(CCM) 50	181.55
50 % (Organic) + 50 % (Inorganic)	180.17
100 % (RDF)	180.40
SE (m) ±	1.06
LSD at 5 %	NS
Main Sub (Interaction)	
SE (m) ±	1.83
LSD at 5 %	NS

The interaction effect between main plot and sub-plot treatments was also non-significant (NS), indicating that the effect of nitrogen management on potassium uptake was consistent across all genotypes and did not interact with genetic background.

The significant variation in potassium content among maize hybrids indicates genotypic differences in nutrient absorption and translocation capacity (33). The higher potassium accumulation in PMH14 reflects its efficient root uptake and better ionic balance maintenance compared to PMH13 and ADV9293(16). The absence of significant variation among nitrogen management practices suggests that potassium uptake was largely unaffected by different nitrogen application methods, likely due to adequate soil potassium availability (15). Slightly higher values under CCM 50 and LCC 5 indicate a potential improvement in nutrient uptake efficiency under precision nitrogen management, though not statistically significant (9). The non-significant interaction between hybrids and nitrogen management confirms that the response of potassium absorption remained uniform across all genotypes under varying nitrogen regimes (14).

Correlation analysis

The correlation analysis (Table 24) revealed that grain yield had strong, highly significant positive correlations with glucose (0.933), number of leaves (0.904), fructose (0.870), plant height (0.870), leaf nitrogen content (0.881), cob length (0.855), sucrose (0.865), leaf area (0.774) and membrane stability index (0.610), while showing a moderate association with total chlorophyll content (0.458). Growth traits were closely interrelated, as plant height correlated strongly with leaves, leaf area, cob length and leaf nitrogen (≥0.80), indicating coordinated vegetative vigor. Soluble sugars were strongly correlated among themselves (r≈0.95-0.96) and with leaf nitrogen (rf≈0.95-0.98), suggesting nitrogen as a key factor for carbohydrate accumulation. Membrane stability index correlated positively with growth, biochemical and yield traits (r≈0.46-0.72), reflecting its importance for productivity. Total chlorophyll showed weaker yet significant relationships with yield, indicating a secondary role compared to nitrogen and sugars. Among macronutrients, nitrogen showed strong positive relationships (r≈0.52-0.82), potassium moderate (r≈0.53-0.60) and phosphorus moderate to weak (r≈0.36-0.52) with growth, sugars and yield, highlighting the role of balanced nutrition, particularly nitrogen, in enhancing physiological status and yield. Stem girth had weak associations, significant only with leaf length and nitrogen, indicating limited linkage with performance. Overall, higher nitrogen and membrane stability promoted chlorophyll and sugar accumulation, driving vegetative vigor and yield improvement.

Conclusion

The study demonstrated that sensor-guided precision nitrogen management (CCM 50, LCC 5) significantly improved maize growth, physiology, biochemical traits and yield compared to conventional fertilization. PMH14 consistently outperformed PMH13 and ADV9293 in morphological, physiological and yield attributes, showing the benefit of combining superior genetics with real-time nutrient application. Sensor-based nitrogen scheduling maximized leaf expansion, chlorophyll content, sugar biosynthesis and nitrogen uptake, enhancing source-sink dynamics for better cob development, grain yield and nitrogen use efficiency. Conventional and partially organic regimes supplied nitrogen less optimally, leading to lower growth and yield. Overall, aligning nitrogen application with crop demand via sensors enhances maize productivity, quality and sustainability.

Table 24. Correlation matrix of agronomic, physiological and biochemical parameters associated with leaf color chart (LCC) and chlorophyll content meter (CCM) based nitrogen management in Maize

	Ph	Nl	Sg	Ll	La	Loc	P	SOP	GOP	FOP	LNC	TCC	MSI	GY	N	P.1	K
Ph	1																
Nl	0.909***	1															
Sg	0.255	0.247	1														
Ll	0.668***	0.552***	0.286*	1													
La	0.837***	0.798***	0.236	0.393**	1												
Loc	0.964***	0.884***	0.26	0.696***	0.834***	1											
P	0.542***	0.53***	0.242	0.449***	0.339*	0.549***	1										
SOP	0.976***	0.935***	0.257	0.645***	0.836***	0.936***	0.514***	1									
GOP	0.941***	0.958***	0.244	0.602***	0.827***	0.925***	0.508***	0.957***	1								
FOP	0.946***	0.911***	0.219	0.62***	0.832***	0.94***	0.459***	0.954***	0.947***	1							
LNC	0.966***	0.938***	0.243	0.651***	0.806***	0.935***	0.522***	0.976***	0.955***	0.958***	1						
TCC	0.375**	0.412**	0.107	0.322*	0.352**	0.463***	0.239	0.369**	0.456***	0.454***	0.427**	1					
MSI	0.678***	0.651***	0.147	0.462***	0.544***	0.653***	0.356**	0.689***	0.677***	0.722***	0.674***	0.29*	1				
GY	0.87***	0.904***	0.266	0.561***	0.774***	0.855***	0.465***	0.865***	0.933***	0.87***	0.881***	0.458***	0.61***	1			
N	0.783***	0.703***	0.321*	0.706***	0.597***	0.817***	0.377**	0.746***	0.749***	0.782***	0.782***	0.421**	0.524***	0.723***	1		
P.1	0.542***	0.53***	0.242	0.449***	0.339*	0.549***	1***	0.514***	0.508***	0.459***	0.522***	0.239	0.356**	0.465***	0.377**	1	
K	0.585***	0.532***	0.076	0.266	0.572***	0.534***	0.236	0.59***	0.571***	0.58***	0.602***	0.207	0.389**	0.528***	0.475***	0.236	1

Ph- Plant height, Nl- No of leaves, Sg- Steam girth, Ll- Leaf length, La- Leaf area, Loc- Length of cob, P- Protein, SOP- Sucrose of plant, GOP- Glucose of plant, FOP- Fructose of plant, LNC- Leaf Nitrogen Content, TCC - Total chlorophyl content, MSI- Membrane stability index, GY- Grain yield, N- Nitrogen, P- Phosphorus, K- Potassium; * ($p < 0.05$): Statistically significant, ** ($p < 0.01$): Highly significant; *** ($p < 0.001$): Very highly significant.

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Authors' contributions

AB contributed to the conceptualisation of the study, carried out data curation, performed the formal analysis and investigation, assisted in developing the methodology, conducted the statistical analysis, wrote the original draft and participated in the writing, reviewing and editing of the manuscript. AP and BP contributed to data curation, carried out the formal analysis and investigation, assisted in developing the methodology and helped in writing the original draft of the manuscript. NR and SM contributed to data curation, carried out the formal analysis and investigation, assisted in developing the methodology, performed the statistical analysis and contributed to the writing, reviewing and editing of the manuscript. All authors reviewed 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 in order 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.

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