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Evaluating Nutrient Uptake and Efficiency in Maize Through Precision Nutrient Management Strategies

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Abstract: Maize is a versatile crop in terms of growing season and use, which produces a sizable amount of biomass in a season and removes an ample quantity of nutrients from the soil. Such a nutrient-exhaustive crop needs an exogenous application of nutrients to meet its needs. Hence, precision nutrient management can be a scientific option for maize. Based on the facts, a field experiment was conducted during the Rabi seasons of 2022-23 and 2023-24 at the P.G. Research Farm of the M. S. Swaminathan School of Agriculture, Odisha, India, to evaluate the nutrient removal and nutrient use efficiency of maize. The experiment was carried out in a randomized block design with 13 treatments, replicated thrice. The treatments were: T_1: RDF (120-60-60 kg ha^{-1} N, P_2O_5 and K_2O), T_2: 125% RDF (150-75-75 kg ha^{-1}), T_3: 75% RDF (90-45-45 kg ha^{-1}), T_4: 150% RDF (180-90-90 kg ha^{-1}), T_5: RDF + nano urea, T_6: 75% RDF + nano urea, T_7: LCC 4-based nitrogen management, T_8: LCC 5-based nitrogen management, T_9: chlorophyll content meter (CCM) sufficiency index 85–90%, T_{10}: CCM sufficiency index 90–95%, T_{11}: nutrient expert (NE) targeted yield 7 t ha^{-1}, T_{12}: NE targeted yield 9 t ha^{-1} and T_{13}: control (0-0-0 kg ha^{-1}). The recommended dose of 120:60:60 kg ha^{-1} N, P_2O_5 and K_2O was applied. The highest nitrogen content in grain and stover was recorded with T_{10} and T_4. However, T_4 recorded the highest P and K content in grain and stover of maize. The highest agronomic use efficiency (AUE) of maize for the primary nutrients was computed with T_2, which was followed by T_9 and T_{12}. The highest partial factor productivity (PFP) for N, P and K was T_{10}, closely followed by T_9, T_{12}, T_4 and T_2. The treatment T_3 recorded the highest nutrient harvest index (NHI) for primary nutrients, followed by T_2 and T_1. However, the highest nutrient content in the post-harvest soil denoted values for N with T_1, P with T_2 and K with T_4 and T_{12}. The results concluded that precision nutrient management with split application in maize with optical sensors and decision support systems can be replicated further in various agroclimatic situations and cropping systems.

Introduction

The agricultural intensification through indiscriminate application of synthetic fertilizers has helped in attaining food security after the fossil fuel-based green revolution, and the adverse effects are visible in the changing climatic scenario (Santosh et al., 2024; Mukesh et al., 2024; Ray et al., 2024, 2025). Agriculture is one of the biggest contributors to global warming and in agriculture, application of synthetic fertilizers leads to various environmental challenges such as nutrient imbalances, soil acidification, groundwater contamination and greenhouse gas emission (Manasa et al., 2021; Chataut et al., 2023).

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The climate extremes, land shrinkage, groundwater depletion and ever-growing population are leading the path towards food and nutritional insecurity (Tchonkouang et al., 2024). Continuation of such a situation is challenging the United Nations target for achieving the "Zero hunger" goal by 2030 (Chappa et al., 2023; Sporchia et al., 2024). Crops belonging to the family of *Poaceae* are the most affected and bring the situation to the brink of food insecurity; they cover a maximum portion of the platter of the global population. Among various cereals, maize (*Zea mays*) is one of the staples which is used as food, feed, fodder and industrial raw material (Maheswari et al., 2025; Sairam et al., 2025a,b). Maize is grown in various agro-climatic conditions, ensuring food security (Sairam et al., 2024a; Maitra et al., 2024). Maize is a C_4 plant, with a capacity of producing a higher amount of biomass in a short duration, which removes 29.9, 13.5 and 32.8 kg ha^{-1} of N, P_2O_5 and K_2O from the soil, proving the nutrient exhaustive property. The conventional practice of blanket application of nutrients doesn't align with the needs of the crop or soil fertility, leading to an unsustainable approach in the long term, with a decrease in economic returns (Maitra, 2020; Chivenge et al., 2022). To combat the limitations, precision nutrient management appears as a sustainable approach which focuses on the right time and right amount of nutrients, which meet the needs of the crop while decreasing the environmental impact and enhancing economic returns (Sairam et al., 2024b; Maitra et al. 2024). Modern agriculture uses technologies such as LCC (leaf colour chart), CCM (chlorophyll content meter), SPAD (soil plant analysis development) meter, GreenSeeker, the NDVI-based (normalized difference vegetation index) sensor, etc., for non-destructive, real-time plant data analysis. Among primary nutrients, nitrogen (N), phosphorus (P) and potassium (K), N is the most exploited fertilizers, which is applied in excess, leading to various environmental degradation, hence, increasing the need for precise management in crops like maize (Anas et al., 2020; Mwadalu et al., 2022).

Despite the over-dose use of synthetic fertilizers, nutrient use efficiency (NUE) in maize remained below 50% leading to substantial losses of nutrients to the environment (Maitra et al., 2001; Zhu et al., 2023). The inefficiency is further exacerbated by climatic vulnerabilities that impact soil health and plant responses. Therefore, the need for precision nutrient management has emerged as a robust and ecologically sustainable approach (Soussi et al., 2024). Further, some parameters such as agronomic efficiency, partial factor productivity, recovery efficiency, etc., provide a better insight into the nutrient absorption, utilization and conversion to the economic yield, especially under the changing climatic scenario (Pramanick et al., 2024). Additionally, a nutrient balance sheet is important for quantifying and tracking the gain or loss of nutrients in the soil and crop system, which can help in identifying inefficiency and for further tailoring of nutrients as per the needs of the crop and soil. Such parameters provide a holistic approach for nutrient dynamics and support evidence-based recommendations for sustainable maize cultivation. Considering the above fact, the study was conducted to evaluate nutrient uptake and efficiency in maize under precision nutrient management strategies.

Materials and Methods

The experiment was carried out at PG Research Farm of M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Odisha, India during *rabi* season of 2022-23 and 2023-24 (Fig. 1). The mean maximum temperature ranged from 28°C to 39°C in 2021-22 and 27°C to 37°C in 2022-23, while the mean minimum temperature varied from13°C to 24°C and 15°C to 22°C, respectively. The mean maximum and minimum relative humidity ranged from 88 to 96% and 39 to 80%, 79 to 91% and 37 to 68% in 2021-2022 and 2022-23, respectively. The total rainfall was 145.9 mm and 71.8 mm in 2021-22 and 2022-23, respectively. The mean sunshine hours recorded during both years were 7 to 9 hours daily. The experimental soil was sandy clay loam with a pH of 6.3, 0.44% and 0.45%, available nitrogen of 233 and 244 kg ha^{-1}, available phosphorus of 12.5 and 12.7 kg ha^{-1}, available potassium of 131.5 and 136.4 kg ha^{-1} for 2021-2022 and 2022-23, respectively. The experiment was laid out in a randomized block design with 13 treatments, replicated thrice. The treatments were: T_1: RDF (120-60-60 kg ha^{-1} N, P_2O_5 and K_2O), T_2: 125% RDF (150-75-75 kg ha^{-1}), T_3: 75% RDF (90-45-45 kg ha^{-1}), T_4: 150% RDF (180-90-90 kg ha^{-1}), T_5: RDF + nano urea, T_6: 75% RDF + nano urea, T_7: LCC 4-based nitrogen management, T_8: LCC 5-based nitrogen management, T_9: chlorophyll content meter (CCM) sufficiency index 85–90%, T_{10}: CCM sufficiency index 90–95%, T_{11}: nutrient expert (NE) targeted yield 7 t ha^{-1}, T_{12}: NE targeted yield 9 t ha^{-1} and T_{13}: absolute control (no fertilizer). The recommended doses of 120:60:60 kg ha^{-1} nitrogen, phosphate and potassium were applied, and standard agronomic practices were followed. Further, to accurately assess soil fertility status, crop nutrient uptake, and the efficiency of applied nutrients, the standard analytical methods were employed. The available N, P and K in the post-harvest soil, total nutrient uptake, nitrogen use efficiency (NUE) in terms of agronomic efficiency (AE), physiological efficiency (PE), nutrient harvest index (NHI), apparent recovery efficiency (ARE), partial factor productivity (PFP) were computed by applying formulae as documented by Sairam *et al*. (2020). The data were analysed as per the standard procedure for analysis of variance as described by Panse and Sukhatme (1985) and Cochran and Cox (1977). The significance of treatments was tested by 'F' Fest. The standard error of mean and LSD at 5% probability level of significance was calculated.

Figure 1. Aerial view of experimental field at 90 DAS.

Result and Discussion

Nutrient content and uptake of maize

The highest nitrogen content in grain was recorded in T_{10} (1.36 %) and T_4 (1.38 %) which were statistically similar with other treatments except T_3, T_6 and T_{13} in the first year. The treatments T_4 and T_{10} remained statistically at par with T_2, T_8, T_{12} and T_9 and was superior to T_1, T_3, T_6, T_{13} and T_5 in the second year (Table 1 and Table 2). The lowest nitrogen content was recorded in T_{13}. Nitrogen content in stover followed a similar trend with the highest N content in T_{10} (0.65 and 0.64 % in the respective years) and T_4 (0.64 and 0.63 % in respective years), which were higher than other treatments in 2022-23, but statistically at par with T_2 in the second year. The highest P content in grain was recorded in T_4 (0.34 and 0.35 % in 2022-23 and 2023-24 respectively) which was statistically similar to T_2 in the first year and significantly higher than to other treatments in 2023-24. The NE-based treatments (T_{11} and T_{12}) recorded the lowest P content as compared to LCC, CCM and RDF-based nutrient management treatments. Moreover, T_{13} recorded the lowest P content in grain (0.25 and 0.24 %) and stover (0.10 and 0.11 %) in respective years. In the case of stover, T_4 and T_2 recorded the highest value of P content and were significantly superior to other treatments. The treatments T_{10} and T_9 performed better than the precision nutrient management treatments and RDF levels; whereas, the NE-based treatments performed similarly to the treatment T_3. Potassium content in grain varied significantly. The treatment T_4 recorded the highest values of K content which were statistically at par with T_2, T_{12} and T_{11} in both years, whereas, T_{13} recorded the lowest. In the case of stover, the highest K content was recorded in T_4 (1.37 and 1.36% in respective years) which was closely followed by T_2, T_{11} and T_{12} and were statistically superior to remaining treatments.

The total uptake was significantly influenced by precision nutrient management in both years (Table 2). The highest N uptake in gain was noted in T_4 (104.2 and 107.6 kg ha^{-1} in the respective years) which was closely followed by T_{10} and T_2 and were statistically at par with remaining treatments, whereas, the lowest nitrogen uptake was recorded in the control (25.51 and 25.49 kg ha^{-1} in 2022-23 and 2023-24, respectively. N uptake in stover and total N uptake also followed the same trend, where the treatment T_4 recorded the highest N uptake by stover (81.39 and 79.35 kg ha^{-1} in the respective years) and total uptake (185.71 and 86.96 kg ha^{-1} in the respective years), which was statistically at par with T_{10} and T_2. In the case of P uptake, T_4 (26.11 and 27.31 kg ha^{-1} in respective years) remained statistically at par with T_{10} (24.14 and 25.61 kg ha^{-1} in respective years) and T_2 (23.58 and 23.75 kg ha^{-1} in respective years). The treatments T_8 and T_{12} remained statistically at par with each other but were inferior to T_2, T_4 and T_{10}. P uptake in stover and total P also followed the same trend. The treatments T_9, T_8 and T_{12} were found to be better as compared to T_1, T_5, T_3, T_6 and T_{13}. The treatment T_{13} recorded the lowest P uptake in grain (6.06 and 6.08 kg ha^{-1}), stover (3.13 and 3.07 kg ha^{-1}) and total (9.20 and 9.15 kg ha^{-1}) in the respective years. The highest K uptake in the grain of maize was recorded with T4 (42.95 and 42.91 kg ha^{-1}), followed by T10 (39.99 and 41.92 kg ha^{-1}) in the respective years and was statistically superior to other treatments. K uptake by maize stover and total K uptake followed a similar trend.

The nutrient content of maize, namely, nitrogen, phosphorus and potassium recorded a directly

Table 1. Effect of precision nutrient management on nitrogen, phosphorous and potassium content in grain and stover during both years.

Content Treatments	N (%)				P (%)				K (%)			
	2021-22		2022-23		2021-22		2022-23		2021-22		2022-23	
	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover
T_{1}	1.28	0.56	1.27	0.54	0.31	0.14	0.30	0.14	0.52	1.26	0.53	1.24
T_{2}	1.35	0.61	1.36	0.62	0.33	0.16	0.33	0.16	0.54	1.35	0.55	1.35
T_{3}	1.17	0.52	1.17	0.50	0.29	0.12	0.30	0.13	0.47	1.20	0.47	1.22
T_{4}	1.36	0.64	1.38	0.63	0.34	0.17	0.35	0.16	0.56	1.37	0.55	1.36
T_{5}	1.29	0.57	1.27	0.56	0.32	0.14	0.32	0.15	0.52	1.26	0.54	1.26
T_{6}	1.19	0.52	1.20	0.52	0.28	0.12	0.29	0.13	0.46	1.22	0.47	1.24
T_{7}	1.28	0.60	1.29	0.61	0.30	0.13	0.31	0.13	0.50	1.25	0.49	1.26
T_{8}	1.33	0.62	1.32	0.62	0.30	0.14	0.31	0.13	0.52	1.28	0.51	1.28
T_{9}	1.33	0.62	1.31	0.61	0.31	0.15	0.32	0.15	0.52	1.28	0.52	1.29
T_{10}	1.36	0.65	1.36	0.64	0.32	0.15	0.33	0.15	0.53	1.27	0.54	1.27
T_{11}	1.33	0.58	1.34	0.56	0.29	0.12	0.29	0.13	0.54	1.32	0.54	1.33
T_{12}	1.35	0.60	1.34	0.61	0.29	0.13	0.30	0.12	0.54	1.35	0.55	1.34
T_{13}	1.04	0.41	1.01	0.43	0.25	0.10	0.24	0.10	0.41	1.07	0.39	1.09
SEm±	0.0342	0.0076	0.0299	0.0099	0.006	0.0021	0.0059	0.0029	0.01	0.0185	0.0112	0.0168
CD (5%)	0.099	0.022	0.0871	0.0288	0.0174	0.0059	0.01717	0.0084	0.0293	0.0539	0.0327	0.0489

Table 2. Effect of precision nutrient management on nitrogen, phosphorus and potassium uptake in grain and stover during both years.

Uptake Treatments	N uptake (kg ha^{-1})						P uptake (kg ha^{-1})						K uptake (kg ha^{-1})					
	2021-22			2022-23			2021-22			2022-23			2021-22			2022-23		
	Grain	Stover	Total	Grain	Stover	Total	Grain	Stover	Total	Grain	Stover	Total	Grain	Stover	Total	Grain	Stover	Total
T_{1}	55.29	38.63	93.92	55.42	38.50	93.92	13.39	9.66	23.04	13.09	10.02	23.11	22.47	86.92	109.39	23.15	88.42	111.57
T_{2}	96.41	65.30	161.71	97.90	72.08	169.98	23.58	17.22	40.80	23.75	18.64	42.39	38.57	144.14	182.71	39.61	156.96	196.57
T_{3}	42.60	25.82	68.42	45.20	28.66	73.86	10.55	5.94	16.49	11.59	7.43	19.02	17.11	59.60	76.72	18.18	69.94	88.12
T_{4}	104.32	81.39	185.71	107.61	79.35	186.96	26.11	21.62	47.73	27.31	20.19	47.50	42.95	174.29	217.24	42.91	171.33	214.24
T_{5}	56.98	40.85	97.82	62.37	39.98	102.35	14.10	10.03	24.13	15.69	10.73	26.42	22.97	90.18	113.16	26.47	89.91	116.38
T_{6}	41.83	28.47	70.30	42.07	29.67	71.74	9.79	6.56	16.35	10.17	7.42	17.60	16.11	66.65	82.76	16.47	70.71	87.18
T_{7}	63.03	45.52	108.54	64.94	47.19	112.13	14.76	9.86	24.62	15.61	10.05	25.66	24.61	94.78	119.38	24.67	97.45	122.12
T_{8}	75.70	55.92	131.62	76.15	55.17	131.32	17.04	12.62	29.66	17.89	12.24	30.13	29.55	115.41	144.96	29.42	113.91	143.33
T_{9}	82.21	61.41	143.62	83.36	61.60	144.96	19.13	14.86	33.99	20.36	15.18	35.55	32.10	126.82	158.92	33.10	130.28	163.38
T_{10}	102.74	79.44	182.19	105.58	80.40	185.98	24.14	18.33	42.47	25.61	18.81	44.42	*39.99*	155.23	195.22	41.92	159.57	201.50
T_{11}	68.63	47.56	116.19	69.36	47.19	116.55	14.96	9.84	24.80	14.95	10.96	25.90	27.86	108.24	136.10	27.89	112.13	140.02
T_{12}	80.92	58.44	139.36	84.17	59.55	143.72	17.44	12.66	30.10	18.71	11.72	30.43	32.45	131.49	163.93	34.56	130.84	165.40
T_{13}	25.51	12.85	38.36	25.49	13.17	38.66	6.06	3.13	9.20	6.07	3.07	9.15	10.03	33.53	43.55	9.92	33.29	43.21
SEm±	2.88	2.43	4.06	4.21	1.93	4.94	0.006	0.0021	1.04	0.0059	0.0029	2.95	0.01	0.0185	5.72	0.0112	0.0168	5.00
CD (5%)	8.41	7.09	11.85	12.27	5.62	14.41	0.0174	0.0059	3.02	0.0171	0.0084	1.01	0.0293	0.0539	16.68	0.0327	0.0489	14.59

proportional relationship with the amount of primary nutrients applied. The treatments with ample dose application of nitrogen, phosphorus and potassium (T_4) resulted in higher tissue content of the nutrients compared to its lesser amount and no application of primary nutrients (Sampathkumar and Pandian, 2010). This justifies the higher N, P and K content of both grain and straw in the treatment T_4 where the highest level of primary nutrients was applied and a greater number of spilt applications of nitrogen (T_{10}) might enable for the ready availability of mineral elements at the root zone, enhancing the uptake of said nutrients for the crop (Nagarjun and Yogananda, 2017). Similarly, treatments with higher grain and straw nutrient concentrations (T_4, T_{10}, and T_2), along with more biomass and grain yield production, resulted in higher nutrient uptake of maize during both years of the experiment (Kumar et al., 2015a).

Treatments with sufficient supply of nitrogen, phosphorus and potassium in terms of quantity and split doses with timely application (T_4 and T_{10}) resulted in higher nutrient uptake of maize (Riar et al., 2023). The treatments with recommended dose of primary nutrients application along with supplementary application of nano urea (T_1, T_3, T_5 and T_6) resulted in values moderately good amount of nutrient content in grain as well as stover, however, due to production of comparatively less biomass and yields than T_4 and T_{10}, there was less uptake of the primary nutrients with later treatments (Bhuiya et al., 2020). The study clearly revealed the beneficial impact of precision nutrient management on nutrient uptake in maize and the synergistic effect of phosphorus and potassium in improving the nutritional quality of the maize grain (Riar et al., 2023).

Table 3. Effect of precision nutrient management on AUE and PUE of nitrogen, phosphorus and potassium during both years.

Treatments	Agronomic use efficiency (kg kg^{-1})						Physiological use efficiency (kg kg^{-1})					
	N		P		K		N		P		K	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T_1	15.8	15.3	31.5	30.6	31.5	30.6	46.7	49.2	93.3	98.3	93.3	98.3
T_2	31.4	31.1	62.8	62.2	62.8	62.2	82.0	88.0	164.0	176.0	164.0	176.0
T_3	12.3	10.7	24.7	21.5	24.7	21.5	33.3	44.4	66.7	88.9	66.7	88.9
T_4	29.1	29.3	58.3	58.5	58.3	58.5	82.2	82.2	164.4	164.4	164.4	164.4
T_5	16.5	19.7	33.1	39.5	33.1	39.5	50.0	53.3	100.0	106.7	100.0	106.7
T_6	13.1	14.8	26.2	29.6	26.2	29.6	37.8	40.0	75.6	80.0	75.6	80.0
T_7	21.7	21.7	41.6	41.7	41.6	41.7	60.0	62.6	115.0	120.0	115.0	120.0
T_8	23.3	23.1	54.3	53.9	54.3	53.9	65.0	65.0	151.7	151.7	151.7	151.7
T_9	26.8	27.4	62.5	63.9	62.5	63.9	75.0	77.9	175.0	181.7	175.0	181.7
T_{10}	31.0	31.7	75.3	77.2	75.3	77.2	86.1	89.1	236.7	245.0	236.7	245.0
T_{11}	20.7	20.0	55.7	53.8	38.5	37.1	59.1	60.6	159.2	163.3	109.9	112.7
T_{12}	31.3	28.9	69.9	63.8	57.3	53.0	70.6	72.7	180.4	185.7	129.5	133.3
T_{13}	-	-	-	-	-	-	-	-	-	-	-	-

Table 4. Effect of precision nutrient management on ARE PFP and nutrient harvest of nitrogen, phosphorus and potassium during both years.

Treatments	Apparent recovery efficiency (kg kg^{-1})						Partial factor productivity (kg kg^{-1})						Nutrient harvest index (%)					
	N		P		K		N		P		K		N		P		K	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T_1	46.3	46.1	23.1	23.3	109.7	113.9	36.0	36.4	72.0	72.8	72.0	72.8	58.9	59.0	58.1	56.6	20.5	20.7
T_2	82.2	87.5	42.1	44.3	185.5	204.5	44.9	45.3	89.9	90.7	89.9	90.7	59.6	57.6	57.8	56.0	21.1	20.2
T_3	33.4	39.1	16.2	21.9	73.7	99.8	39.0	38.9	78.0	77.8	78.0	77.8	62.3	61.2	64.0	60.9	22.3	20.6
T_4	81.9	82.4	42.8	42.6	193.0	190.0	41.9	43.2	83.9	86.3	83.9	86.3	56.2	57.6	54.7	57.5	19.8	20.0
T_5	49.6	53.1	24.9	28.8	116.0	122.0	36.8	40.8	73.5	81.7	73.5	81.7	58.3	60.9	58.4	59.4	20.3	22.7
T_6	35.5	36.8	15.9	18.8	87.1	97.7	40.4	43.0	80.9	86.0	80.9	86.0	59.5	58.6	59.9	57.8	19.5	18.9
T_7	61.0	63.9	25.7	27.5	126.4	131.5	42.8	43.7	82.0	83.8	82.0	83.8	58.1	57.9	60.0	60.8	20.6	20.2
T_8	66.6	66.2	34.1	35.0	169.0	166.9	40.6	41.2	94.8	96.2	94.8	96.2	57.5	58.0	57.5	59.4	20.4	20.5
T_9	75.2	75.9	41.3	44.0	192.3	200.3	44.1	45.5	103.0	106.2	103.0	106.2	57.2	57.5	56.3	57.3	20.2	20.3
T_{10}	87.2	89.3	55.5	58.8	252.8	263.8	46.5	47.3	127.8	130.0	127.8	130.0	56.4	56.8	56.8	57.7	20.5	20.8
T_{11}	59.0	59.0	31.8	34.2	130.4	136.4	39.1	39.1	105.3	105.3	72.7	72.7	59.1	59.5	60.3	57.7	20.5	19.9
T_{12}	70.6	73.5	37.3	38.0	154.3	156.7	42.0	43.7	107.1	111.6	76.9	80.1	58.1	58.6	57.9	61.5	19.8	20.9
T_{13}	-	-	-	-	-	-	-	-	-	-	-	-	66.5	65.9	65.9	66.3	23.0	23.0

Nutrient use efficiency

Agronomic Use Efficiency (AUE) of maize for nitrogen, phosphorus and potassium was evaluated as per the yield difference from control and total nutrient applied (Table 3). The highest AUE was recorded for T_2 (31.4 and 31.1 kg kg^{-1}), T_9 (31.0 and 31.7 kg ka^{-1}) and T_{12} (31.3 and 28.9 kg kg^{-1}) in the respective years, whereas, the lowest AUE was recorded for T_1, T_5 and T_6. In the case of phosphorus and potassium, highest AUE was recorded for T_{10} (75.3 and 77.2 kg kg^{-1}) for both the years which was followed by T_{12} and T_2. Physiological Use Efficiency (PUE) was recorded as the highest value with T10 for nitrogen (86.7 and 89.0 kg kg-1), phosphorus (236.7 and 245.0 kg kg-1), and potassium (236.7 and 245.0 kg kg-1), which was followed by T_4, T_2, and T_9 in both years (Table 3). For nitrogen, the lowest PUE was recorded in T_3 and T_6. A similar trend was observed for P and K. The highest apparent recovery efficiency (ARE) was recorded in T_{10} for N (87.1 and 89.2 %), P (55.4 and 58.5 %), and K (252.7 and 263.8 %) in both years, which was closely followed by T_4, T_2, T_9 and T_{12}. The least value of ARE was recorded for T_7 and T_{11} (Table 4).

The partial factor productivity (PFP) derived by considering the nutrient uptake in treatment plots with nutrient uptake in control plot based on total nutrients applied. The result showed that the highest value of PFP among the nutrient management treatments for nitrogen, phosphorus and potassium was recorded with the treatment T_{10} which was closely followed by T_9, T_{12}, T_4 and T_2. In the case of the highest PFP of phosphorus and potassium, the treatment T_{10} was closely followed by T_{12}, T_{13} and T_2. The application of nano urea did not contribute in increasing the PFP of nitrogen.

The nutrient harvest index (NHI) of maize was computed and presented in Table 5. The NHI of N, P and K registered the highest values in the treatment T_{13}. Among the nutrients applied treatments, the highest NHI of N, P and K was noted with the treatment T_3 and it was

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closely followed by T_2 and T_1 and they expressed a very marginal difference. The precision nutrient management treatments and application of nano nitrogen did not influence the improvement of the NHI of all three primary nutrients. The application of N, P and K, i.e., T_2 and T_4 recorded a marginal increase in the NHI compared to the presession nutrient management treatments.

The results revealed a similar trend showing the importance of the application of primary nutrients through precession nutrient management tools, namely, CCM SI-based N management, NE-based nutrient management for a target yield, LCC-based N management for improving the nutrient use efficiency in maize compared to the blanket application of recommended dose of fertilizers (Kumar et al*.,* 2015b; Joshi et al*.*, 2018; Prakasha et al., 2020). Due to the split application of nitrogen through T_8: LCC5-based nitrogen management, T_9 and T_{10} improved the nitrogen use efficiency during both years of the study, probably because of the split application of nitrogen (Riar et al., 2023; Jat et al., 2021). Apart from these, the site-specific application of nutrients through NE also improved the phosphorus and potassium use efficiency of maize (Nagarjun and Yogananda, 2017). Due to the least availability of nutrients and more uptake, the treatment with lower dose application (T_3) had a marginally higher nutrient use efficiency compared to T_1 and T_2 (Riar et al., 2023).

Table 5. Effect of precision nutrient management on nitrogen balance during 2021-22.

Nitrogen balance 2021-22							
Treatments	Initial available soil N (kg ha^{-1})	Applied N (kg ha^{-1})	Total N uptake (kg ha^{-1})	Estimated available N (kg ha^{-1})	Actual available N (kg ha^{-1})	Apparent N kg ha^{-1} (loss / gain)	Net N kg ha^{-1} (loss / gain)
	A	B	C	D=(A+B)-C	E	F= (D-E)	G=(A-E)
T_1	236	120	93.9	262.1	222.1	-40.0	-13.92
T_2	236	150	161.7	224.3	220.6	-3.7	-15.4
T_3	236	90	68.4	257.6	208.7	-48.9	-27.3
T_4	236	180	185.7	230.3	215.4	-14.9	-20.6
T_5	236	120	97.8	258.2	217.2	-41.0	-18.82
T_6	236	90	70.3	255.7	210.7	-45.0	-25.3
T_7	236	115	108.5	242.5	213.8	-28.7	-22.2
T_8	236	140	131.6	244.4	216.7	-27.7	-19.3
T_9	236	140	143.6	232.4	214.8	-17.6	-21.2
T_{10}	236	165	182.2	218.8	218.6	-0.2	-17.4
T_{11}	236	132	116.2	251.8	219.3	-32.5	-16.7
T_{12}	236	143	139.4	239.6	217.5	-22.1	-18.5
T_{13}	236	0	38.4	197.6	199.0	1.4	-37

Nutrient availability and nutrient balance

Considering the initial available nutrients in the soil and post-harvest available nutrients in the soil, the nutrient balance (net gain/loss) was computed for two different years of the experiment (Tables 5, 6, 7, 8, 9, 10). The nitrogen availability and nitrogen balance showed a remarkable difference due to various levels of N doses. The available nitrogen in the soil varied between 222.1 kg ha^{-1} to 199.0 kg ha^{-1} during 2021-22 and 224.3 kg ha^{-1} to 206.3 kg ha^{-1} during 2022-23 (Table 5 and Table 6). The highest available nitrogen in post-harvest soil was registered with the treatment T_1 and it was closely followed by T_9, T_{10}, T_2, T_4 and T_{12}. Further, the treatment T_{13} recorded the lowest nitrogen availability during both the years. The nitrogen balance during both the years followed a similar trend and there was a loss in soil N availability ranging from 13.92 kg ha^{-1} to 37.07 kg ha^{-1} and 16.7 kg ha^{-1} to 34.7 kg ha^{-1} respectively in 2021-22 and 2022-23. The loss of nitrogen was noted more in treatments where less quantity of nitrogen was applied.

The highest availability of phosphorus in post-harvest soil was recorded with treatment T_2 (13.9 kg ha^{-1} and 14.3 kg ha^{-1}) during both years of the experiment, respectively (Table 7 and Table 8). Further, this treatment was closely followed by T_{10}, T_9, T_4 during both the years of the study. The least phosphorus availability was noted in T_{13} which was followed by T_3, T_6, T_{12} and T_{11}. The impact of nutrient management practices had both positive and negative effects on soil phosphorus balance. The phosphorus balance among the treatments varied between the gain of 1.4 kg ha^{-1} and the loss of 1.1 kg ha^{-1} during 2021-22 and 1.6 kg ha^{-1} and the loss of 0.9 kg ha^{-1} during 2022-23. The highest gain in soil phosphorus availability was recorded in T_4, followed by T_2. However, the maximum loss of phosphorus in post-harvest

Table 6. Effect of precision nutrient management on nitrogen balance during 2022-23.

Nitrogen balance 2022-23							
Treatments	Initial available soil N (kg ha^{-1})	Applied N (kg ha^{-1})	Total N uptake (kg ha^{-1})	Estimated available N (kg ha^{-1})	Actual available N (kg ha^{-1})	Apparent N kg ha^{-1} (loss / gain)	Net N kg ha^{-1} (loss / gain)
	A	B	C	D=(A+B)-C	E	F= (D-E)	G=(A-E)
T_1	241	120	93.9	267.1	224.3	-42.8	-16.7
T_2	241	150	170.0	221.0	222.8	1.8	-18.2
T_3	241	90	73.9	257.1	214.4	-42.7	-26.6
T_4	241	180	187.0	234.0	221.3	-12.7	-19.7
T_5	241	120	102.4	258.7	217.5	-41.2	-23.5
T_6	241	90	71.7	259.3	217.3	-42.0	-23.7
T_7	241	115	112.1	243.9	216.4	-27.5	-24.6
T_8	241	140	131.3	249.7	219.8	-29.9	-21.2
T_9	241	140	145.0	236.0	223.5	-12.5	-17.5
T_{10}	241	165	186.0	220.0	221.2	1.2	-19.8
T_{11}	241	132	116.6	256.5	219.7	-36.8	-21.3
T_{12}	241	143	143.7	240.3	216	-24.3	-25
T_{13}	241	0	38.7	202.3	206.3	4.0	-34.7

Table 7. Effect of precision nutrient management on phosphorus balance during 2021-22.

Phosphorus balance 2021-22							
Treatments	Initial available soil P (kg ha^{-1})	Applied P (kg ha^{-1})	Total P uptake (kg ha^{-1})	Estimated available P (kg ha^{-1})	Actual available P (kg ha^{-1})	Apparent P kg ha^{-1} (loss / gain)	Net P kg ha^{-1} (loss / gain)
	A	B	C	D=(A+B)-C	E	F= (D-E)	G=(A-E)
T_1	12.6	60	23.0	49.6	13	-36.6	0.4
T_2	12.6	75	40.8	46.8	13.9	-32.9	1.3
T_3	12.6	45	16.5	41.1	12.5	-28.6	-0.1
T_4	12.6	90	47.7	54.9	14	-40.9	1.4
T_5	12.6	60	24.1	48.5	13.5	-35.0	0.9
T_6	12.6	45	16.4	41.3	12.3	-29.0	-0.3
T_7	12.6	60	24.6	48.0	13.1	-34.9	0.5
T_8	12.6	60	29.7	42.9	13.3	-29.6	0.7
T_9	12.6	60	34.0	38.6	13.6	-25.0	1
T_{10}	12.6	60	42.5	30.1	13.8	-16.3	1.2
T_{11}	12.6	49	24.8	36.8	12.2	-24.6	-0.4
T_{12}	12.6	56	30.1	38.5	12.5	-26.0	-0.1
T_{13}	12.6	0	9.2	3.4	11.5	8.1	-1.1

soil was observed in T_{13} during both the years of the study.

Among the nutrient management treatments, the maximum availability of potassium in the post-harvest soil was noted with the treatment T_4, T_{12} and T_{11} (Table 9 and Table 10). Further, these treatments were closely followed by T_9 and T_8 during the both the years of the experiment. The lowest potassium availability in the post-harvest soil was recorded in T_{13} and it was followed by T_3 and T_6. The precision application of potassium through nutrient expert-based for a target yields (T_{11} and T_{12}) were found to be more efficient in improving the potassium availability in the post-harvest soil compared to other presession nutrient management tools. The ample dose of potassium application (T_4) also improved the potassium availability during both the years.

The nutrient availability of post-harvest soil and nutrient balance calculated for two consecutive years of experiment for nitrogen, phosphorus and potassium showed a dissimilar trend among each primary nutrient (Nagarjun and Yogananda, 2017). Maize being a heavy nutrient feeder with more requirement of nitrogen depleted the soil nitrogen with a loss of 13.9 kg ha^{-1} to 37.0 kg ha^{-1} during first year and 16.7 kg ha^{-1} to 34.7 kg ha^{-1} during second year depending on the treatment specificity (Kumar et al., 2015b). Compared to the blanket application of RDF, the precession nutrient management treatments resulted in an optimum available nitrogen even after a heavy uptake of the said nutrient by the crop under the precession nutrient management treatments. The findings clearly established the impact of precession nutrient tools on sustaining the soil nutrient status as well as maintaining the soil productivity (Pramanick et al., 2022). In case of phosphorus and potassium availability in post experimental soil, the highest availability was observed in the treatments with higher level of phosphorus and potassium application (T_2

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Table 8. Effect of precision nutrient management on phosphorus balance and available phosphorus during 2022-23.

Phosphorus balance 2022-23							
Treatments	**Initial available soil P (kg ha^{-1})**	**Applied P (kg ha^{-1})**	**Total P uptake (kg ha^{-1})**	**Estimated available P (kg ha^{-1})**	**Actual available P (kg ha^{-1})**	**Apparent P kg ha^{-1} (loss / gain)**	**Net P kg ha^{-1} (loss / gain)**
	A	**B**	**C**	**D=(A+B)-C**	**E**	**F= (D-E)**	**G=(A-E)**
T_1	12.8	60	23.1	49.7	13.4	-36.3	0.6
T_2	12.8	75	42.4	45.4	14.3	-31.1	1.5
T_3	12.8	45	19.0	38.8	12.6	-26.2	-0.2
T_4	12.8	90	47.5	55.3	14.4	-40.9	1.6
T_5	12.8	60	26.4	46.4	13.9	-32.5	1.1
T_6	12.8	45	17.6	40.2	12.5	-27.7	-0.3
T_7	12.8	60	25.7	47.1	13.5	-33.6	0.7
T_8	12.8	60	30.1	42.7	13.7	-29.0	0.9
T_9	12.8	60	35.6	37.3	14	-23.3	1.2
T_{10}	12.8	60	44.4	28.4	14.2	-14.2	1.4
T_{11}	12.8	49	25.9	35.9	12.3	-23.6	-0.5
T_{12}	12.8	56	30.4	38.4	12.6	-25.8	-0.2
T_{13}	12.8	0	9.2	3.7	11.9	8.3	-0.9

Table 9. Effect of precision nutrient management on potassium balance and available potassium during 2021-22.

Potassium balance 2021-22							
Treatments	**Initial available soil K (kg ha^{-1})**	**Applied K (kg ha^{-1})**	**Total K uptake (kg ha^{-1})**	**Estimated available K (kg ha^{-1})**	**Actual available K (kg ha^{-1})**	**Apparent K kg ha^{-1} (loss / gain)**	**Net K kg ha^{-1} (loss / gain)**
	A	**B**	**C**	**D=(A+B)-C**	**E**	**F= (D-E)**	**G=(A-E)**
T_1	137.8	60	109.4	88.4	132.6	44.2	-5.2
T_2	137.8	75	182.7	30.1	136.4	106.3	-1.4
T_3	137.8	45	76.7	106.1	131.2	25.1	-6.6
T_4	137.8	90	217.2	10.6	141.4	130.8	3.6
T_5	137.8	60	113.2	84.6	135.3	50.7	-2.5
T_6	137.8	45	82.8	100.0	131.6	31.6	-6.2
T_7	137.8	60	119.4	78.4	135.5	57.1	-2.3
T_8	137.8	60	145.0	52.8	137.4	84.6	-0.4
T_9	137.8	60	158.9	38.9	137.3	98.4	-0.5
T_{10}	137.8	60	195.2	2.6	136.4	133.8	-1.4
T_{11}	137.8	71	136.1	72.7	139.4	66.7	1.6
T_{12}	137.8	78	163.9	51.9	140.4	88.5	2.6
T_{13}	137.8	0	43.6	94.3	122.4	28.2	-15.4

Table 10. Effect of precision nutrient management on potassium balance and available potassium during 2022-23.

Potassium balance 2022-23							
Treatments	**Initial available soil K (kg ha^{-1})**	**Applied K (kg ha^{-1})**	**Total K uptake (kg ha^{-1})**	**Estimated available K (kg ha^{-1})**	**Actual available K (kg ha^{-1})**	**Apparent K kg ha^{-1} (loss / gain)**	**Net K kg ha^{-1} (loss / gain)**
	A	**B**	**C**	**D=(A+B)-C**	**E**	**F= (D-E)**	**G=(A-E)**
T_1	141.3	60	111.6	89.7	137	47.3	-4.3
T_2	141.3	75	196.6	19.7	140	120.3	-1.3
T_3	141.3	45	88.1	98.2	135	36.8	-6.3
T_4	141.3	90	214.2	17.1	145	127.9	3.7
T_5	141.3	60	116.4	84.9	138	53.1	-3.3
T_6	141.3	45	87.2	99.1	136	36.9	-5.3
T_7	141.3	60	122.1	79.2	139	59.8	-2.3
T_8	141.3	60	143.3	58.0	141	83.0	-0.3
T_9	141.3	60	163.4	37.9	141	103.1	-0.3
T_{10}	141.3	60	201.5	-0.2	140	140.2	-1.3
T_{11}	141.3	71	140.0	72.3	143	70.7	1.7
T_{12}	141.3	78	165.4	53.9	142	88.1	0.7
T_{13}	141.3	0	43.2	98.1	128	29.9	-13.3

and T_4). The enhanced P and K application probably enhanced the availability of P in the past-harvest soil. The supply of inorganic fertilizers to the plants ensured ready availability at the root zone, which might result in less dependency of the crop on inherent soil fertility as well as phosphorus and potassium supplying capability of the soil (Pooniya et al., 2015). Similar to the nitrogen availability and balance, the phosphorus and potassium balance were also noted with higher values in all the precision nutrient management treatments (T_9, T_{10}, T_{11}, and T_{12}) compared to T_1 and T_3 (Riar et al., 2023).

Conclusion

The present investigation demonstrated that nutrient content, uptake, use efficiency and post-harvest soil nutrient availability after different nutrient management practices significantly influenced maize cultivation. Treatments receiving an ample and balanced supply of primary nutrients, particularly T_4 (higher NPK dose with split application) and T_{10} (SPAD-based nitrogen management), consistently resulted in higher nutrient concentration in both grain and stover, which in turn enhanced total nutrient uptake across both years of study. These treatments also improved phosphorus and potassium uptake, highlighting the synergistic role of adequate nutrient supply in enhancing the nutritional quality of maize. Thus, the study establishes that precision nutrient management, particularly with an ample dose of nitrogen application (T_4) and precision nitrogen management with optimum P and K (T_{10}), not only enhances nutrient content and uptake of maize but also improved nutrient use efficiency while sustaining soil nutrient balance. Adoption of such site-specific and split application strategies can therefore serve as a sustainable nutrient management practice for improving maize productivity, nutrient use efficiency, and soil health in intensive cropping systems.

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Conflict of Interest

The authors declare no conflict of interest.

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