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RESEARCH ARTICLE

Foliar application of nano-fertilizers enhances growth, nutrient uptake and agronomic efficiency in maize (*Zea mays* L.)

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Abstract

This study investigated the impact of foliar-applied nano fertilizers on growth, nutrient uptake and agronomic efficiency in maize (*Zea mays* L.) during the kharif seasons of 2021 and 2022 in Karnataka, India. The experiment employed a randomized complete block design with fourteen treatments, comparing various combinations of conventional fertilizers (CF), nano-nitrogen, nano-phosphorus and water-soluble fertilizers (WSF). Dry matter accumulation, nutrient uptake patterns and agronomic efficiency were assessed at different growth stages. Results demonstrated that treatment T9 (75 % recommended dose of nitrogen, phosphorus (RDNP) through CF + 2 foliar sprays of nano-nitrogen and phosphorus) consistently showed superior performance in dry matter accumulation (44.77 g/plant) and nutrient uptake. Nitrogen content in leaves decreased steadily from 60 to 120 days after sowing (DAS), while phosphorus levels remained relatively stable. The highest agronomic efficiency of nitrogen (AEN) was observed in T8 (67.9 %), while T12 exhibited maximum phosphorus efficiency (136 %). Statistical analysis revealed significant positive correlations between nutrient use efficiency and crop yield ($r = 0.64$ for AEN; $r = 0.55$ for AEP). The study demonstrates that integrating nano fertilizers with reduced conventional fertilizer dose (75 % RDNP) can maintain or enhance crop productivity while improving nutrient use efficiency. These findings suggest a promising approach for sustainable nutrient management in maize production systems, potentially reducing conventional fertilizer requirements without compromising yield.

Keywords: foliar application; maize yield; nano fertilizers; nutrient use efficiency

Introduction

Maize (*Zea mays* L.), a versatile cereal crop, has gained significant importance in global agriculture due to its diverse applications in food, feed and industrial sectors. Ranking third in both output and productivity after wheat and rice, maize has experienced consistent expansion in its cultivation area across India (1). This growth is primarily driven by increasing demand in the food and feed sectors, as well as its potential as a biofuel crop (2). While predominantly cultivated during the kharif (monsoon) season, maize's photosensitivity allows for its adaptability to diverse climatic conditions, enabling cultivation throughout the kharif, rabi (winter) and summer seasons as well, spanning a wide geographic range in India.

The cultivation of maize requires substantial nutrients, often exceeding the inherent reserves present in the soil. To address this deficiency, farmers commonly resort to applying fertilizers to the soil or employing foliar spraying techniques (3). However, the global food production and distribution systems face mounting pressures due to the interplay of climate change, population growth and diminishing availability of arable land and freshwater resources (4). These challenges are particularly acute in developing countries, where agricultural productivity is crucial for food security and economic stability (5). To combat these challenges, the implementation of technological advancements and substantial modifications to existing global food production processes may offer potential solutions. Precision agriculture, which includes the use of advanced fertilizer technologies like sensors, GIS-based site-specific applications and nano encapsulated nutrients, has emerged as a promising approach to optimize resource use and improve crop yields (6).

Nutrient management forms an integral component of production management systems. The profitability of crop production hinges upon understanding and applying appropriate nutrient quantities at each growth stage, as well as comprehensively assessing the soil's nutrient supply capacity. This is particularly crucial for maize, which has high nutrient requirements, especially for nitrogen, phosphorus and potassium (7). Contemporary agricultural practices heavily rely on elevated levels of agrochemicals, particularly synthetic chemical fertilizers, to achieve optimal growth and productivity. The use of nano fertilizers in combination with traditional nitrogen fertilizers has immense scope to improve crop yields (8). However, these artificial fertilizers do not necessarily enhance crop productivity or plant nutrient utilization efficiency (NUE). The macronutrients nitrogen, phosphorus and potassium exhibit low NUE values, ranging from 30 % to 35 %, 18 % to 20 % and 35 % to 40 %, respectively. This inefficiency not only results in economic losses for farmers but also contributes to environmental pollution through nutrient runoff and greenhouse gas emissions (9). Furthermore, more than half of the applied fertilizers fail to reach their intended targets due to processes such as photolysis, hydrolysis, leaching and microbial immobilization and degradation (10). This low efficiency of conventional fertilizers has spurred research into alternative nutrient delivery systems that can improve NUE while reducing environmental impacts.

In recent years, nanoscience and nanotechnology have emerged as promising fields for addressing these challenges in agriculture. Nano fertilizers, which are either artificially synthesized or modified iterations of conventional fertilizer components, offer several advantages over traditional bulk fertilizers. These include enhanced nutrient utilization efficiency, increased stress tolerance in crops and improved agricultural yields (11, 12). Nano fertilizers can be synthesized through various methods, including chemical, physical and biological approaches. They can be derived from different vegetative or reproductive parts of plants or engineered from inorganic materials (13). The unique properties of nanomaterials, such as their high surface area to volume ratio and enhanced reactivity, contribute to their potential benefits in agriculture. Researchers suggest that emerging nano strategies, such as nano fertilizers, may prove more effective in enhancing fertilizer utilization compared to conventional bulk fertilizers (14). This improved efficiency is attributed to the ability of nanoparticles to penetrate plant tissues more easily and their potential for controlled release of nutrients (15). Additionally, nano fertilizers significantly improve the physico-chemical and biological properties of soil, largely due to their substantial surface area and potential interactions with soil microorganisms (16).

The potential benefits of nano fertilizers extend beyond improved nutrient efficiency. Studies have shown that they can enhance plant growth, increase chlorophyll content and improve overall plant health (17). Moreover, the use of nano fertilizers could lead to a reduction in the total amount of fertilizer applied, potentially decreasing the environmental footprint of agricultural practices (18). Despite the potential benefits of nano fertilizers, there is insufficient data to conclusively determine their efficacy, particularly when applied through foliar spraying. The mechanisms of nano fertilizer uptake, translocation within plants and their long-term effects on soil health and ecosystem functioning are areas that require further investigation (19).

This study aims to evaluate the impact of nano fertilizers on maize growth and yield components. By exploring the use of nano fertilizers, this research seeks to contribute to the development of more efficient and sustainable agricultural practices, addressing the growing need for increased crop yields while minimizing environmental impact and maximizing resource utilization. The findings of this study could have significant implications for sustainable agriculture, particularly in developing countries where optimizing nutrient use efficiency is crucial for food security and economic development. Moreover, this research contributes to the broader field of nanotechnology in agriculture, paving the way for future innovations in crop nutrition and management strategies.

Material and Methods

Experimental site and soil characteristics

A field experiment was conducted during the kharif (monsoon) seasons of 2021 and 2022 in Shikaripura, Karnataka, India. The research site was situated at 14°28'N latitude, 75°32'E longitude and an elevation of 603 m above sea level. This location falls within the southern transition zone of Karnataka, characterized by semi-arid tropical climate.

The soil at the experimental site was classified as sandy loam, with a particle composition of 68 % sand, 15 % silt and 17 % clay. This soil texture is common in many agricultural regions of Karnataka and is generally suitable for maize cultivation. The soil exhibited mildly acidic properties with a pH of 6.5, which is within the optimal range for maize growth (5.8-7.0). The organic carbon content was moderate at 0.60 %, indicating reasonable soil fertility. The electrical conductivity (EC) was measured at 0.048 dSm^{-1}, suggesting low salinity levels that are non-detrimental to maize growth.

Soil nutrient analysis revealed medium availability of nitrogen (N), phosphorus (P) and potassium (K) at levels of 275, 48.24 and 198 kg ha^{-1}, respectively. These levels fall within the medium range for agricultural soils in the region, as classified by the Karnataka state department of agriculture.

Climatic conditions

The cumulative precipitation recorded during the crop growth period was 691 mm in 2021 and 822 mm in 2022, averaging 756.5 mm over the two-year study period. This rainfall pattern is typical for the region during the kharif season (India Meteorological Department, 2022). The average monthly maximum temperature ranged from 27.5 °C in July to 30 °C in October, while the minimum temperature varied between 19.8 °C and 21.5 °C. Relative humidity fluctuated between 79 % and 92 %. These climatic conditions are generally favorable for maize cultivation, as the crop thrives in warm temperatures with adequate moisture (19).

Experimental design and treatments

The experiment employed a randomized complete block design (RCBD) with three replications, a standard approach in agricultural field trials to account for soil heterogeneity (20). The treatments included various combinations of CF, nano-nitrogen, nano-phosphorus and WSF. The recommended dose of fertilizer (RDF) for maize in the region was applied at 180 kg N ha^{-1}, 100 kg phosphorus pentoxide (P_2O_5) ha^{-1} and 50 kg potassium oxide (K_2O) ha^{-1}, consistent with local agricultural extension recommendations, treatment details was mentioned in the Table 1.

Planting and crop management

Maize (variety: MAH 14-5) was manually sown with a plant-to-plant spacing of 30 cm and a row-to-row spacing of 60 cm, resulting in a plant population of approximately 55,555 plants ha^{-1}. This spacing is consistent with recommendations for optimal maize yield in the region. Thinning was performed to maintain the desired plant population.

Weed management was carried out manually throughout the growing season to minimize competition for resources. Irrigation was provided using the furrow method as

Table 1. Treatment details

Treatments	Treatment details
T1	100 % RDF through conventional fertilizers
T2	50 % RDN through CF + 3 foliar sprays of nano-nitrogen
T3	75 % RDN through CF + 2 foliar sprays of nano-nitrogen
T4	100 % RDN through CF + 1 foliar spray of nano-nitrogen
T5	50 % RDP through CF + 3 foliar sprays of nano-phosphorus
T6	75 % RDP through CF + 2 foliar sprays of nano-phosphorus
T7	100 % RDP through CF + 1 foliar spray of nano-phosphorus
T8	50 % RDNP through CF + 3 foliar sprays of nano-nitrogen and phosphorus
T9	75 % RDNP through CF + 2 foliar sprays of nano-nitrogen and phosphorus
T10	100 % RDNP through CF + 1 foliar spray of nano-nitrogen and phosphorus
T11	50 % RDNP through CF + 3 foliar sprays of WSF (12:61:0)
T12	75 % RDNP through CF + 2 foliar sprays of WSF (12:61:0)
T13	100 % RDNP through CF + 1 foliar spray of WSF (12:61:0)
T14	Absolute control

Note: RDF: Recommended dose of fertilizer, RDN: Recommended dose of nitrogen, RDP: Recommended dose of phosphorus, RDNP: Recommended dose of nitrogen phosphorus

needed, supplementing rainfall to maintain optimal soil moisture conditions for maize growth.

Fertilizer applications

Conventional fertilizers were applied as urea (46 % N), single super phosphate (16 % P_2O_5) and potassium sulphate (50 % K_2O). In treatments receiving 100 % RDF through conventional fertilizers (T1, T4, T7, T10 and T13), full dose of P and K was applied during bed preparation, while N was split-applied with 50 % at bed preparation and the remaining 50 % at tassel initiation and silking stages. This split application of N is a common practice to improve nitrogen use efficiency in maize.

For treatments with reduced CF rates (T2, T5, T8 and T11), 50 % of the RDF was applied as a basal dose. In treatments T3, T6, T9 and T12, the full dose of P and K and 50 % of N were applied as basal, with the remaining 25 % N applied at the knee-high stage, for better understanding of the treatments, how much percent of nutrient was applied were shown in the Table 2.

Nano fertilizers and water-soluble fertilizers

The nano-urea and nano-diammonium phosphate (DAP) used were manufactured by Indian farmers fertilizer cooperative limited (IFFCO). Nano-urea particles ranged from 20-50 nm in size, with an average of 30-40 nm and a specific surface area of 60-80 m^2/g. Nanoparticles were coated with hydrophobic silica to improve dispersion and prevent premature degradation. Nano-DAP had similar specifications. Their small size and surface area enhance nutrient solubility and plant absorption (21-24). The water-soluble fertilizer used had a nutrient ratio of 12:61:0 (N:P:K), applied as foliar sprays in treatments T11-T13.

Statistical analysis

The collected data were subjected to analysis of variance (ANOVA) using an F-test at a 5 % significance level, following the methods (25). This statistical approach allows for the determination of significant differences among treatments. When significant differences were detected, means were separated using the least significant difference (LSD) test at $p \leq 0.05$. All statistical analyses were performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). The normality of data distribution was checked using the Shapiro-Wilk test and homogeneity of variances was assessed using Levene's test prior to ANOVA.

Nutrient uptake by crop

Plant analysis: Plant samples were taken after spraying of nano -N and nano-NP at 30, 60 and 90 days of sowing. Plant samples were collected from each treatment separately, dried and powdered by using mixer grinder with stainless steel blade. The powdered samples were kept in airtight containers for further chemical analysis. These samples were used for analysis of N, P and K.

Digestion of plant samples: One-gram plant sample was pre-digested overnight with nitric acid and kept for digestion with di-acid mixture of nitric acid and perchloric acid (9:4). The filtered digested material was made up to 50 mL volume with 6 N hydrochloric acid (HCl) and was used for the analysis of all mineral elements except nitrogen.

Nitrogen uptake: Nitrogen content was estimated by modified micro-Kjeldhal's method and expressed in percentage (26). Nitrogen uptake (kg ha^{-1}) by crop was calculated for each treatment separately using the following formula.

$$\text{Nitrogen uptake (kg ha}^{-1}\text{)} = \frac{\text{Nitrogen content (\%)}}{100} \times \text{Dry matter (Kg ha}^{-1}\text{)} \quad \text{(Eqn. 1)}$$

Phosphorus uptake: Phosphorus content in the digested plant sample was estimated by Vanadomolybdate phosphoric yellow colour method in nitric acid medium and the colour intensity was measured at 430 nm wavelength (25). It is calculated using the following formula.

$$\text{Phosphorus uptake (kg ha}^{-1}\text{)} = \frac{\text{Phosphorus content (\%)}}{100} \times \text{Dry matter (Kg ha}^{-1}\text{)} \quad \text{(Eqn. 2)}$$

Table 2. Treatment wise nutrient application table (Basal and top dressing nutrients)

Treatment number	Nitrogen fertilizer		Phosphorus fertilizer	Potash fertilizer
	Basal	Top dressing	Basal	Basal
T1, T4, T7, T10 and T13	50 %	50 %	100 %	100 %
T2, T5, T8 and T11	50 %	-	50 %	100 %
T3, T6, T9 and T12	50 %	25 %	75 %	100 %

Nutrient use efficiency (NUE): NUE is defined as the amount of product produced per unit of nutrients used. This means nutrient efficiency is the amount of dry matter produced per unit of nutrient applied or absorbed. NUE can be defined as the relative yield of a genotype on deficient soil, compared with its yield at optimum nutrition.

Agronomic efficiency (AE): The AE is defined as the economic production obtained per unit of nutrient applied. It can be calculated with the help of the following equation and expressed as kg kg^{-1}.

$$AE\ (kg\ kg^{-1}) = \frac{\text{Grain yield of fertilized plot (kg) - Grain yield of control plot (kg)}}{\text{Quantity of nutrient applied (kg)}} \quad \text{(Eqn. 3)}$$

Agronomic efficiency can be calculated for a single nutrient (N, P and K) or for multiple nutrients (N + P + K).

Agronomic efficiency of nitrogen (AEN):

$$AE_N\ (kg\ kg^{-1}) = \frac{\text{Grain yield of fertilized plot (kg) - Grain yield of control plot (kg)}}{\text{Quantity of nitrogen applied (kg)}} \quad \text{(Eqn. 4)}$$

Agronomic efficiency of phosphorus (AEP):

$$AEP\ (kg\ kg^{-1}) = \frac{\text{Grain yield of fertilized plot (kg) - Grain yield of control plot (kg)}}{\text{Quantity of phosphorus applied (kg)}} \quad \text{(Eqn. 5)}$$

Results

Dry matter accumulation in leaves and stems by application nano and water-soluble fertilizers

Dry matter accumulation (DMA) in leaves varied significantly ($p < 0.05$) across treatments (Table 3). Treatment T10 (100 % RDNP through CF + 1 foliar spray of nano-nitrogen and phosphorus) exhibited superior performance with the highest dry matter accumulation in leaves (41.40 g/plant) and stems (80.47 g/plant) at 120 DAS, demonstrating a 141.3 % and 107.5 % increase over the absolute control (T14), respectively. Nano-fertilizer combinations (T10) showed the highest DMA, suggesting improved nutrient uptake. Treatment T9 (75 % RDNP through CF + 2 foliar sprays of nano-nitrogen and phosphorus) achieved nearly equivalent results (41.65 g/plant in leaves and 79.87 g/plant in stems at 120 DAS), indicating that multiple applications of nano fertilizers at reduced rates can compensate for lower base fertilizer application. Notably, treatments T2-T4 (nano-nitrogen variants) and T5-T7 (nano-phosphorus variants) individually showed moderate improvements over conventional treatment T1, but their combined application in treatments T8-T10 demonstrated pronounced synergistic effects on dry matter accumulation. This suggests that nitrogen and phosphorus in nano form work complementarily to enhance photosynthetic efficiency and metabolic processes (25). The water-soluble fertilizer treatments (T11-T13) performed better than conventional fertilization but were less effective than equivalent nano fertilizer treatments (T8-T10), likely due to differences in nutrient release kinetics and cellular penetration efficiency. These findings align with previous studies reporting enhanced growth parameters in maize under nano-fertilizer applications (27, 28). The results underscore the potential of nano fertilizers in optimizing nutrient use efficiency while maintaining or improving crop productivity.

Nitrogen, phosphorus uptake in leaves and stem by application of nano and water-soluble fertilizers

Nitrogen uptake in leaves

Leaf nitrogen uptake differed significantly ($p < 0.05$) among treatments (Table 4). At 60 DAS, treatment T9 demonstrated superior nitrogen uptake (35.59 kg/ha), followed closely by T10 (34.89 kg/ha) and T8 (31.48 kg/ha). This represents a 385 %, 376 % and 329 % increase over the absolute control (T14; 7.33 kg/ha), respectively. The conventional fertilizer treatment (T1) showed moderate nitrogen uptake (30.39 kg/ha) but was substantially outperformed by the nano fertilizer combinations. At 90 DAS, the trend continued with T9 maintaining the highest nitrogen uptake (34.67 kg/ha), followed by T10 (31.80 kg/ha) and T8 (31.50 kg/ha). Interestingly, by 120 DAS, T9 continued to demonstrate exceptional nitrogen uptake retention (31.44 kg/ha), while a substantial decline was observed in T10 (19.63 kg/ha), suggesting that multiple applications of nano fertilizers at reduced rates (75 %) might provide more sustained nitrogen availability throughout the crop cycle compared to a single application at 100 % rate. This aligns with findings from recent research (29).

Phosphorus uptake in leaves

Phosphorus uptake followed trends similar to nitrogen but with lower absolute value. At 60 DAS, T9 again demonstrated the highest phosphorus uptake (5.14 kg/ha), followed by T10 (4.82 kg/ha) and T8 (4.64 kg/ha), representing increases of 404 %, 372 % and 355 % over the control (T14: 1.02 kg/ha), respectively. The conventional treatment (T1) showed moderate phosphorus uptake (3.67 kg/ha) but was substantially lower than the nano-fertilizer combinations. By 90 DAS, T9 maintained the highest phosphorus uptake (5.69 kg/ha), followed by T10 (5.53 kg/ha) and T8 (5.23 kg/ha). At 120 DAS, T9 and T8 retained high phosphorus levels (5.60 and 5.24 kg/ha, respectively), while T10 showed a slight decline (4.66 kg/ha) (30).

Comparative analysis of treatment effects

The water-soluble fertilizer treatments (T11-T13) demonstrated significantly lower nutrient uptake ($p<0.05$) compared to equivalent nano-fertilizer treatments (T8-T10), indicating superior efficacy of nano formulations. Furthermore, the combined application of nano-nitrogen and phosphorus (T8-T10) consistently outperformed individual applications of nano-nitrogen (T2-T4) or nano-phosphorus (T5-T7), indicating synergistic effects between these nutrients in nano form. The statistical parameters standard error mean (SEM), critical difference (CD), coefficient of variation (CV) confirm the reliability and significance of these treatment differences ($p<0.05$).

These findings suggest that nano fertilizers, particularly

Table 3. Dry matter accumulation in leaves and stem 60, 90 and 120 DAS by application of nano and water-soluble fertilizers through foliar spray

Treatments	Dry matter accumulation in leaves (g/plant) 60 DAS	Dry matter accumulation in leaves (g/plant) 90 DAS	Dry matter accumulation in leaves (g/plant) 120 DAS	Dry matter accumulation in stem (g/plant) 60 DAS	Dry matter accumulation in stem (g/plant) 90 DAS	Dry matter accumulation in stem (g/plant) 120 DAS
T1	29.39	35.09	37.47	63.81	67.82	70.01
T2	26.48	32.24	34.53	48.57	52.7	54.48
T3	29.12	35.06	37.62	60.14	63.94	65.77
T4	31.29	37.55	40.15	67.86	71.7	73.61
T5	27.49	32.82	34.83	56.9	60.84	63.03
T6	30.7	36.36	39.17	67.96	71.97	74.33
T7	31.11	37.07	39.86	69.2	73.05	75.46
T8	29.55	34.94	37.37	65.78	69.65	71.77
T9	33.57	39.02	41.65	73.95	77.42	79.87
T10	33.03	38.91	41.4	74.23	77.93	80.47
T11	19.31	25.25	27.16	49.71	53.67	55.42
T12	25.7	31.22	33.21	58.46	62.68	64.69
T13	30.8	36.13	38.68	67.17	71.16	73.47
T14	11.16	16.08	17.16	33.46	37.98	38.78
Sem ±	1.25	1.39	1.45	2.3	2.31	2.38
CD (*p*=0.05)	3.63	4.05	4.21	6.69	6.73	6.92
CV (%)	7.8	7.22	7.02	6.51	6.15	6.13

Note: DAS- Days after sowing

Table 4. Nitrogen and phosphorus uptake in leaves by application of nano and water-soluble fertilizers

Treatments	Nitrogen uptake in leaves (kg/ha) 60 DAS	Nitrogen uptake in leaves (kg/ha) 90 DAS	Nitrogen uptake in leaves (kg/ha) 120 DAS	Phosphorus uptake in leaves (kg/ha) 60 DAS	Phosphorus uptake in leaves (kg/ha) 90 DAS	Phosphorus uptake in leaves (kg/ha) 120 DAS
T1	30.39	28.41	19.10	3.67	4.59	4.62
T2	24.41	29.32	25.85	3.48	4.04	4.06
T3	29.01	28.12	21.24	3.82	4.34	4.44
T4	23.69	24.87	20.75	4.24	4.80	4.75
T5	29.34	30.35	25.01	4.10	4.60	4.49
T6	31.12	30.06	19.69	4.50	5.10	5.06
T7	28.53	27.54	21.56	4.36	4.78	4.92
T8	31.48	31.50	27.27	4.64	5.23	5.24
T9	35.59	34.67	31.44	5.14	5.69	5.60
T10	34.89	31.80	19.63	4.82	5.53	4.66
T11	18.97	19.41	13.97	2.46	3.03	3.15
T12	24.44	20.49	11.19	3.18	3.63	3.73
T13	27.89	18.42	11.04	3.58	4.07	4.21
T14	7.33	6.43	4.37	1.02	1.40	1.43
Sem ±	1.67	1.92	2.13	0.21	0.26	0.34
CD (*p*=0.05)	4.85	5.59	6.18	0.6	0.76	1.00
CV (%)	10.73	12.91	18.95	9.43	10.42	13.85

Note: DAS- Days after sowing

at 75 % recommended dose with multiple foliar applications, can significantly enhance nutrient uptake efficiency compared to conventional and water-soluble fertilizers. This improved nutrient acquisition directly correlates with the enhanced dry matter accumulation observed in previous data, highlighting the potential of nano fertilizer technology to optimize nutrient use efficiency in sustainable agricultural systems (31-33).

Nitrogen uptake in stem

Stem nitrogen uptake varied significantly (Table 5). At 60 DAS, treatment T9 exhibited the highest nitrogen accumulation (78.52 kg/ha), closely followed by T10 (78.37 kg/ha) and T8 (70.14 kg/ha). These values represent substantial increases of 249 %, 248 % and 212 % over absolute control (T14: 22.51 kg/ha), respectively. The conventional fertilizer treatment (T1) showed moderate nitrogen uptake (65.64 kg/ha) but was significantly outperformed by the nano-fertilizer combinations. At 90 DAS, T9 maintained superior nitrogen uptake (69.01 kg/ha), followed by T10 (63.41 kg/ha) and T8 (62.76 kg/ha). At 120 DAS, T9 demonstrated remarkable nitrogen retention (60.38 kg/ha), substantially higher than all other treatments, while T8 (52.45 kg/ha) and T10 (44.58 kg/ha) showed moderate retention.

Phosphorus uptake in stem

The phosphorus uptake dynamics in stem tissues exhibited similar treatment compared to nitrogen. At 60 DAS, treatment T9 again demonstrated superior phosphorus accumulation (11.35 kg/ha), followed by T10 (10.84 kg/ha) and T8 (10.35 kg/ha), representing increases of 277 %, 260 % and 244 % over the control (T14: 3.01 kg/ha), respectively. The conventional treatment (T1) showed moderate phosphorus uptake (7.97 kg/ha), substantially lower than the nano-fertilizer combinations. At 90 DAS, the trend remained consistent with T9 maintaining the highest phosphorus levels (11.30 kg/ha), followed by T10 (11.08 kg/ha) and T8 (10.43 kg/ha). By 120 DAS, T9 retained the highest phosphorus content (10.76 kg/ha), followed by T10 (10.69 kg/ha) and T8 (10.06 kg/ha).

Comparative analysis of treatment effects

The water-soluble fertilizer treatments (T11-T13) demonstrated significantly lower nutrient uptake in stems compared to equivalent nano-fertilizer treatments (T8-T10), despite similar application rates. This disparity suggests superior efficacy of nano formulations in facilitating nutrient translocation into plant tissues. Furthermore, combined application of nano-nitrogen and phosphorus (T8-T10) consistently outperformed individual applications of nano-nitrogen (T2-T4) or nano-phosphorus (T5-T7), indicating synergistic effects between these nutrients when applied in nano form. Notably, T9 consistently outperformed T10, particularly for nitrogen retention at 120 DAS (60.38 vs.

Table 5. Nitrogen and phosphorus uptake in stem by application of nano and water-soluble fertilizers

Treatments	Nitrogen uptake in stem l (kg/ha) 60 DAS	Nitrogen uptake in stem (kg/ha) 90 DAS	Nitrogen uptake in stem (kg/ha) 120 DAS	Phosphorus uptake in stem (kg/ha) 60 DAS	Phosphorus uptake in stem (kg/ha) 90 DAS	Phosphorus uptake in stem (kg/ha) 120 DAS
T1	65.64	54.74	35.33	7.97	8.90	8.67
T2	44.58	47.98	40.79	6.38	6.61	6.42
T3	59.53	51.09	36.77	7.90	7.91	7.76
T4	52.09	47.35	38.09	9.17	9.13	8.69
T5	60.68	55.76	45.19	8.50	8.54	8.15
T6	69.29	59.75	37.83	10.00	10.10	9.58
T7	63.54	54.45	40.91	9.70	9.42	9.32
T8	70.14	62.76	52.45	10.35	10.43	10.06
T9	78.52	69.01	60.38	11.35	11.30	10.76
T10	78.37	63.41	44.58	10.84	11.08	10.69
T11	49.13	41.43	28.49	6.32	6.42	6.42
T12	55.80	41.62	21.92	7.24	7.29	7.27
T13	60.66	36.39	20.78	7.78	7.97	7.96
T14	22.51	14.80	9.75	3.01	3.28	3.21
Sem ±	3.83	3.63	3.46	0.41	0.44	0.45
CD (*p*=0.05)	11.14	10.55	10.05	1.18	1.29	1.30
CV (%)	11.19	12.56	16.33	8.48	9.10	9.42

Note: DAS- days after period sowing

44.58 kg/ha), suggesting that multiple applications at reduced rates provide more efficient and sustained nutrient availability than single applications at higher rates.

The statistical parameters (SEM: 3.46-3.83 for N, 0.41-0.45 for P; CD: 10.05-11.14 for N, 1.18-1.30 for P; CV: 11.19-16.33 % for N, 8.48-9.42 % for P) confirm the reliability and statistical significance of the observed treatment differences.

Nitrogen and phosphorus content in plant by application of nano and water-soluble fertilizers

Nitrogen content in plants

Nitrogen content varied significantly across treatments at all growth stages (Table 6). At 60 DAS, treatments T5 (50 % RDP through CF + 3 foliar sprays of nano-phosphorus) and T8 (50 % RDNP through CF + 3 foliar sprays of nano-nitrogen and phosphorus) exhibited the highest nitrogen concentration (1.92 %), followed closely by T9 (1.91 %) and T10 (1.90 %). These values represent substantial increases of 58.7 %, 58.7 %, 57.9 % and 57.0 % over absolute control (T14: 1.21%), respectively. The conventional fertilizer treatment (T1) showed moderate nitrogen content (1.86 %). At 90 DAS, T5 maintained the highest nitrogen concentration (1.66 %), followed by T2 (1.63 %) and T8 (1.62 %). While, at 120 DAS, T9 demonstrated superior nitrogen retention (1.36 %), followed by T2 (1.35 %) and T8 (1.32 %). Nano-nitrogen formulations improve nitrogen retention in plant tissues through enhanced cellular uptake and reduced volatilization losses (34, 35). Nitrogen content declined from 60 to 120 DAS in all treatments.

Treatment T9 maintained consistently high nitrogen content across all growth stages and achieved the highest concentration at 120 DAS despite using 25 % less base fertilizer than conventional treatment T1. This demonstrates the efficiency of balanced nano fertilizer applications at reduced rates, on the superior efficacy of nano fertilizers in maintaining nutrient homeostasis in plant systems.

Phosphorus content in plants

Phosphorus content showed similar but smaller treatment effects than nitrogen. At 60 DAS, treatments T8 and T9 demonstrated the highest phosphorus concentration (both 0.28 %), followed by T5 (0.27 %) and T6 and T10 (both 0.26 %). These values represent increases of 75 %, 75 %, 68.8 % and 62.5 % over the control (T14: 0.16 %), respectively. The conventional treatment (T1) showed moderate phosphorus content (0.22 %). At 90 DAS, T8 maintained the highest phosphorus level (0.27 %), followed by T9 and T10 (both 0.26 %). By 120 DAS, T8 retained the highest phosphorus concentration (0.25 %), followed by T9 and T10 (both 0.24 %).

Table 6. Nitrogen and phosphorus content in plant by application of nano and water-soluble fertilizers

Treatments	Nitrogen content in plant 60 DAS (%)	Nitrogen content in plant 90 DAS (%)	Nitrogen content in plant 120 DAS (%)	Phosphorus content in plant 60 DAS (%)	Phosphorus content in plant 90 DAS (%)	Phosphorus content in plant 120 DAS (%)
T1	1.86	1.46	0.92	0.22	0.24	0.22
T2	1.66	1.63	1.35	0.24	0.23	0.21
T3	1.79	1.44	1.01	0.24	0.22	0.21
T4	1.37	1.19	0.93	0.24	0.23	0.21
T5	1.92	1.66	1.29	0.27	0.25	0.23
T6	1.83	1.49	0.91	0.26	0.25	0.23
T7	1.65	1.33	0.97	0.25	0.23	0.22
T8	1.92	1.62	1.32	0.28	0.27	0.25
T9	1.91	1.60	1.36	0.28	0.26	0.24
T10	1.90	1.47	1.00	0.26	0.26	0.24
T11	1.77	1.39	0.93	0.23	0.22	0.21
T12	1.73	1.20	0.61	0.22	0.21	0.20
T13	1.63	0.92	0.51	0.21	0.20	0.20
T14	1.21	0.70	0.45	0.16	0.15	0.15
Sem ±	0.09	0.09	0.08	0.01	0.01	0.01
CD (*p*=0.05)	0.28	0.26	0.24	0.02	0.02	0.02
CV (%)	9.54	11.32	15.04	5.5	5.71	5.92

Note: DAS- Days after sowing

Unlike nitrogen, phosphorus content exhibited relative stability across growth stages, with only slight decreases from 60 to 120 DAS in most treatments. This stability could be attributed to the reduced mobility of phosphorus in plant systems compared to nitrogen, as well as the enhanced solubility and sustained release characteristics of nano-phosphorus formulations.

Comparative analysis of treatment effects

The combined application of nano-nitrogen and phosphorus (T8-T10) consistently resulted in higher nutrient concentrations compared to individual applications of nano-nitrogen (T2-T4) or nano-phosphorus (T5-T7), indicating synergistic effects between these nutrients when applied in nano form. Notably, treatments with multiple applications at reduced rates (T8 and T9) demonstrated superior nutrient maintenance at 120 DAS compared to single applications at higher rates (T10), suggesting that frequency of application plays a crucial role in optimizing nutrient use efficiency with nano fertilizers.

The water-soluble fertilizer treatments (T11-T13) showed inferior performance compared to equivalent nano-fertilizer treatments (T8-T10), particularly at later growth stages. By 120 DAS, T13 (100 % RDNP with 1 spray of WSF) maintained only 0.51 % nitrogen and 0.20 % phosphorus, substantially lower than T10 (100 % RDNP with 1 spray of nano fertilizer), which maintained 1.00 % nitrogen and 0.24 % phosphorus.

The statistical parameters (SEM: 0.08-0.09 for N, 0.01 for P; CD: 0.24-0.28 for N, 0.02 for P; CV: 9.54-15.04 % for N, 5.5-5.92 % for P) confirm the reliability and statistical significance of the observed treatment differences. These findings collectively suggest that nano fertilizers, particularly at 75 % recommended dose with multiple foliar applications, can significantly enhance and maintain nutrient concentrations in plant tissues compared to conventional and water-soluble fertilizers.

Agronomic efficiency of nitrogen by application of nano and water-soluble fertilizers

The agronomic efficiency of nitrogen (AEN) varied significantly across different treatments, demonstrating the comparative effectiveness of various fertilizer combinations (Fig. 1). Treatment T8 exhibited the highest AEN of 67.9 %, aligns with enhanced nutrient use efficiency with combined nano-fertilizer applications other (36). The second-highest efficiency was observed in T2 (57.3 %), utilizing 50 % RDN with three foliar sprays of nano-nitrogen, supporting the effectiveness of reduced conventional fertilizer doses supplemented with nano -formulations. Treatments T9 (47.5 %) and T11 (45.4 %) showed moderate efficiency levels, while conventional fertilizer alone (T1) recorded significantly lower efficiency (30.4 %). This pattern corroborates with the findings of those who documented superior nutrient utilization through nano fertilizer integration (37). Statistical analysis revealed significant differences between treatments ($p < 0.05$), denoted by letters (a-f), with treatments sharing the same letter not differing significantly. The control treatment (T14) showed minimal efficiency, establishing a clear baseline for comparison. These results align with comprehensive studies, demonstrating that strategic integration of nano-fertilizers with reduced conventional fertilizer doses can significantly enhance nitrogen use efficiency (38). Notably, treatments combining 50 % recommended dose with three foliar sprays consistently outperformed higher base doses with fewer sprays, suggesting optimal nutrient delivery through frequent, smaller applications of nano-fertilizer (39). The box plot

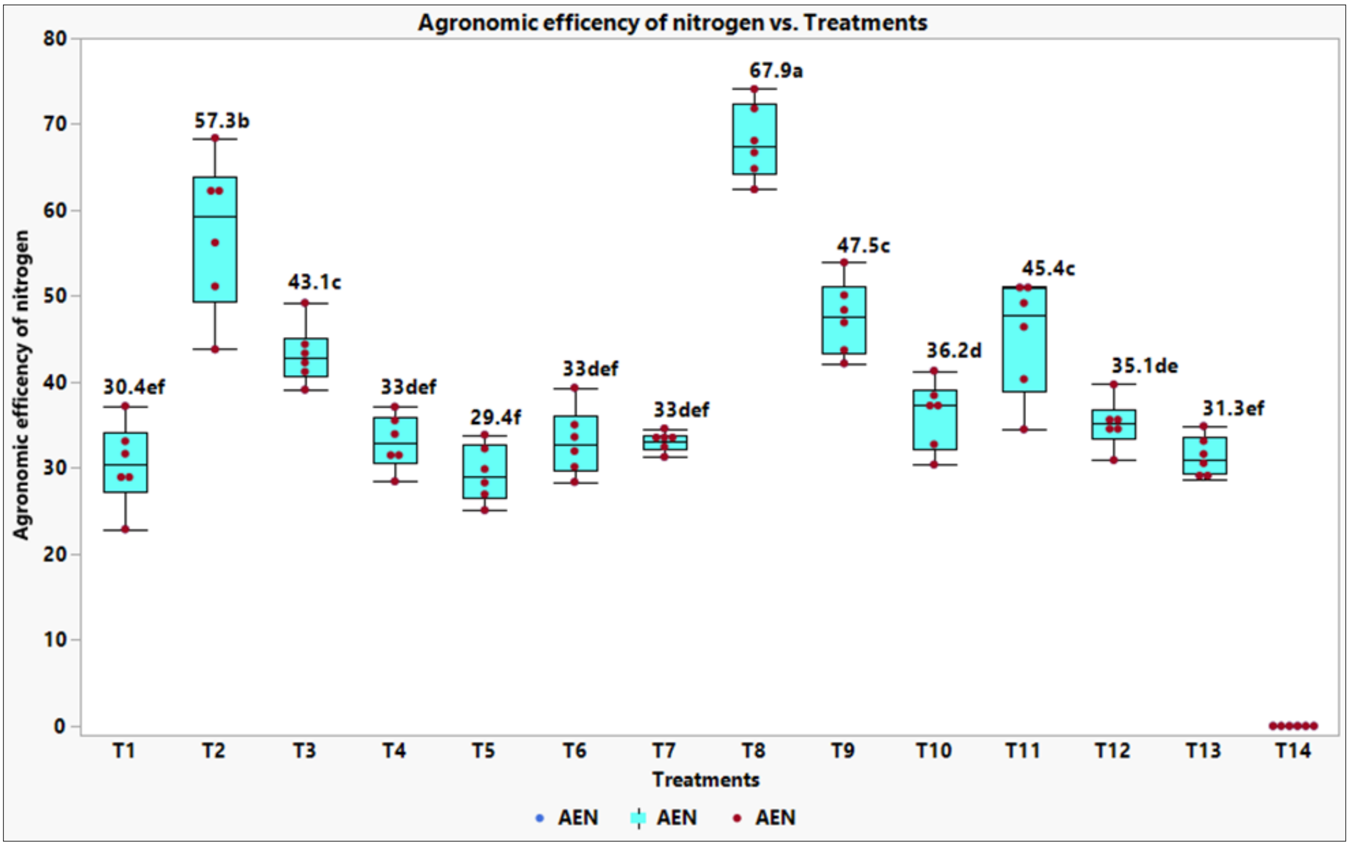

Fig. 1. Agronomic efficiency of nitrogen in different treatments (AEN-agronomic efficiency of nitrogen) by application of nano and water-soluble fertilizers.

representation indicates the variability within treatments, with T8 showing both the highest mean efficiency and relatively consistent performance across replicates.

Agronomic efficiency of phosphorus by application of nano and water-soluble fertilizers

The agronomic efficiency of phosphorus (AEP) demonstrated significant variations across treatments, with notably higher efficiencies in nano-fertilizer combinations (Fig. 2). Treatment T12 exhibited the highest AEP (136a %), followed by T8 (135a %), both showing statistically similar results at $p < 0.05$. Higher phosphorus uptake efficiency through nano-formulations Treatment T5 showed substantial efficiency (116b %). The moderate efficiency range was observed in treatments T9 (94.8c %) and T11 (88.5c %), while conventional fertilizer alone (T1) showed relatively lower efficiency (60.9e %). Statistical analysis revealed distinct groupings (denoted by letters a-e), with treatments sharing the same letter showing no significant differences. The control treatment (T14) maintained minimal efficiency, establishing a clear baseline. These results were align with comprehensive research (40). Notably, treatments T8 and T12, which implemented reduced conventional fertilizer doses (50 % RDNP) with nano-fertilizer supplementation, demonstrated significantly higher efficiency compared to higher conventional doses. The box plot distribution indicates consistent performance within top-performing treatments, with T8 and T12 showing both high mean efficiency and relatively low variability across replicates, suggesting reliable enhancement of phosphorus utilization through nano-fertilizer integration.

Relationship between agronomic efficiency of nitrogen (AEN), agronomic efficiency of phosphorus (AEP) and crop yield

The three-dimensional response surface demonstrates the intricate relationship between AEN, AEP and crop yield (Fig. 3). The graph depicts an ellipsoidal surface spanning AEN values from -20 to 80 kg/ha and AEP values from 0 to 150 kg/ha, with yield responses ranging from 0 to 8000 kg/ha. The convex nature of the response surface indicates a strong synergistic interaction between nitrogen and phosphorus use efficiencies in determining crop yield. Maximum grain yields approaching 8000 kg/ha were achieved when AEN values ranged between 40-60 kg/ha and AEP values were between 80-100 kg/ha, suggesting an optimal zone for nutrient use efficiency. The scattered black dots on the surface represent actual experimental data points from various treatment combinations outlined in the treatment table, including different ratios of conventional fertilizers, nano-nutrients and foliar applications. The gradual decline in yield at both lower and higher efficiency values indicates that both insufficient and excessive nutrient use efficiencies can be detrimental to crop productivity, emphasizing the importance of balanced nutrient management for optimal yield outcomes.

This correlation graph illustrates the complex interplay between AEN, AEP and crop yield (Fig. 4 and Table 7). It provides valuable insights for researchers investigating nutrient management strategies to optimize agricultural productivity.

The graph consists of six scatter plots, each displaying the relationship between two variables. The top left plot shows the correlation between AEN and yield, with r = 0.6199 indicating a moderately strong positive correlation. The top right plot depicts the correlation between AEP and yield, with r = 0.6438 suggesting an even stronger positive relationship. These findings align with established principles in plant nutrition, where both nitrogen and phosphorus play crucial roles in plant growth and development.

The bottom left and right plots explore the direct correlation between AEN and AEP, with r = 0.6199 and r =

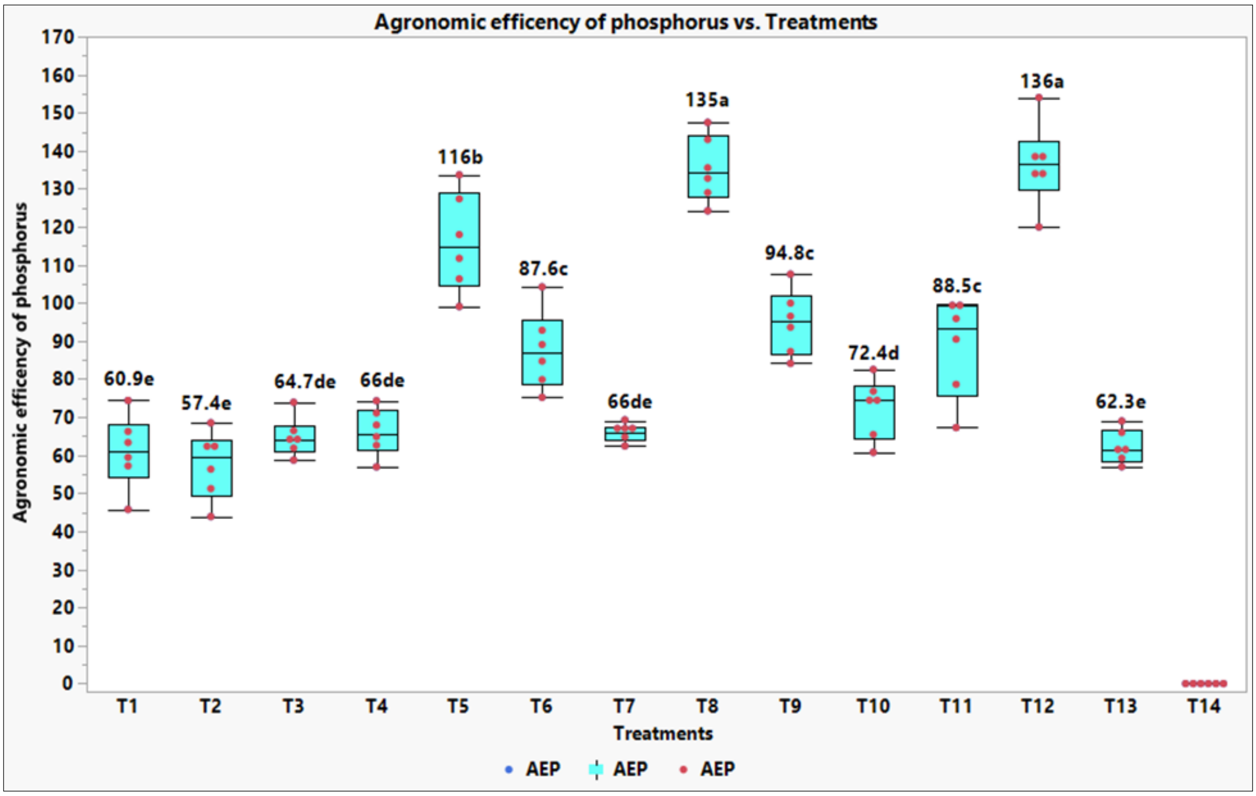

Fig. 2. Agronomic efficiency of phosphorus in different treatments (AEP- agronomic efficiency of phosphorus) by application of nano and water-soluble fertilizers.

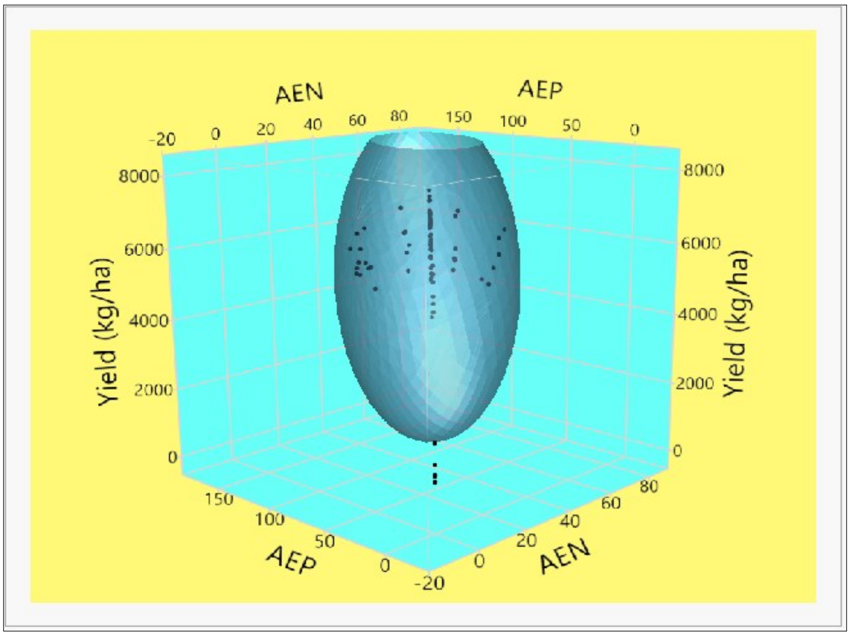

Fig. 3. Relationship between agronomic efficiency of nitrogen (AEN), agronomic efficiency of phosphorus (AEP) and crop yield by application of nano and water-soluble fertilizers.

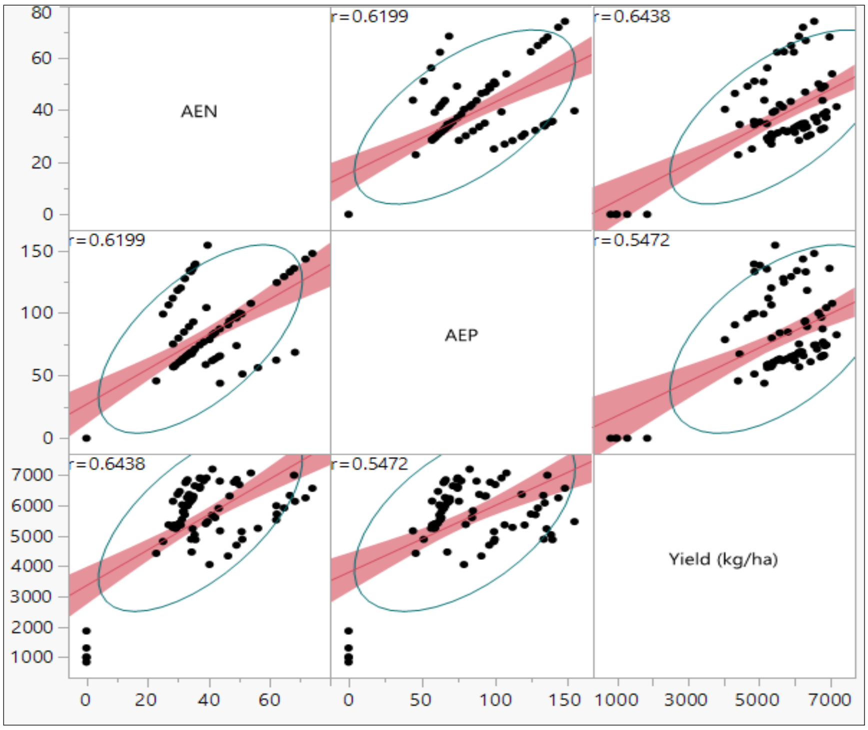

Fig. 4. Correlation between agronomic efficiency of nitrogen (AEN), agronomic efficiency of phosphorus (AEP) and crop yield by application of nano and water-soluble fertilizers.

Table 7. CI of Correlation of agronomic efficiency of nitrogen, phosphorus and yield

Variable	By variable	Correlation	Lower 95 %	Upper 95 %
AEP	AEN	0.6199	0.4677	0.7364
Yield (kg/ha)	AEN	0.6438	0.4981	0.7541
Yield (kg/ha)	AEP	0.5472	0.3770	0.6816

0.5472, respectively (Fig. 4). This suggests that improving the efficiency of one nutrient can have a positive impact on the efficiency of the other, underscoring the importance of a balanced nutrient management approach.

The central plots further elucidate the synergistic effects of AEN and AEP on crop yield. The three-dimensional response surface demonstrates that maximum yields are achieved when both AEN and AEP values are within an optimal range, typically between 40-60 kg/ha for AEN and 80-100 kg/ha for AEP (Fig. 3). This highlights the critical role of balancing nitrogen and phosphorus use efficiency to realize the full yield potential of the crop.

Nutrient composition in maize grains by application of nano and water-soluble fertilizers

The data shows that the application of nano-fertilizers has significantly impacted the nutrient composition of maize grains. For instance, the protein content ranged from 7.42 % in absolute control (T14) to 8.92 % in the treatment with 75% RDNP through CF + 2 foliar sprays of nano-nitrogen and phosphorus (T9). Similarly, the fiber content varied from 10.40 % in the treatment with 50 % RDNP through CF + 3 foliar sprays of WSF (T11) to 11.93 % in the treatment with 75 % RDNP through CF + 2 foliar sprays of nano-nitrogen and phosphorus (T9). The carbohydrate content was highest in the treatment with 75% RDN through CF + 2 foliar sprays of nano-nitrogen (T3 and T4) at 68.57 % and lowest in the treatment with 50 % RDNP through CF + 3 foliar sprays of WSF (T11) at 65.45 %. These variations in the nutrient composition can be attributed to the different levels and combinations of nano-fertilizers used in the treatments (Table 8).

Benefit cost analysis of the treatments

The nano-fertilizer treatments demonstrated superior economic performance compared to conventional fertilization approaches. Treatment T_9 (75% RDF through conventional fertilizers + 2 foliar sprays of nano -N and P) achieved the highest net return of Rs. 111,014 with a benefit-cost ratio of 2.64, representing the most economically viable option. Among individual nano-fertilizer applications, nano-phosphorus treatments consistently outperformed nano-nitrogen treatments. Treatment T_6 (75 % RDF + 2 foliar sprays of nano-P) generated Rs. 99,813 net return with a B:C ratio of 2.48, while the corresponding nano-N treatment (T_3) yielded Rs. 84,129 with a B:C ratio of 2.24.

The conventional 100 % RDF treatment (T_1) showed moderate profitability with Rs. 48,496 net return and 1.71 B:C ratio. Water-soluble fertilizer treatments (T_{11}-T_{13}) performed poorly, with net returns ranging from Rs. 38,454 to Rs. 69,591 and B:C ratios between 1.59-2.02. The absolute control (T_{14}) expectedly showed the lowest economic returns (Rs. 3,420 net return, 1.08 B:C ratio). The results indicate that integrating reduced conventional fertilizer rates (75% RDF) with targeted nano-fertilizer foliar applications provides optimal economic returns while potentially reducing overall fertilizer input costs. The combination of nano -N and P treatments consistently demonstrated the highest profitability among all treatments, shown in Table 9.

Discussion

The study demonstrates that nano-fertilizers improve nutrient utilization and productivity in maize. The results reveal that integrating nano-nitrogen and nano-phosphorus fertilizers with reduced conventional fertilizer doses can substantially enhance agricultural performance. Specifically, treatment T9 (75% recommended nutrient dose through conventional fertilizers + 2 foliar sprays of nano-N and P) consistently emerged as the most effective treatment across multiple critical parameters.

When nano-formulated nitrogen and phosphorus fertilizers are applied to maize foliage, their uptake and translocation occur through multiple cellular mechanisms. These nanoparticles initially penetrate the leaf surface via two primary routes: crossing the waxy cuticle layer and entering through stomatal openings to reach the mesophyll tissue. Once inside the leaf tissue, the nanoparticles follow distinct transport pathways based on their physical characteristics. Smaller nanoparticles (typically under 50 nm) predominantly utilize the symplastic route, moving through plasmodesmata - microscopic channels connecting adjacent cells that range from 2-20 nm in diameter. This pathway allows nanoparticles to travel through the living cellular network, accumulating within the

Table 8. Nutrient composition in maize grains by application of nano fertilizers

Treatments	Protein %	Fat %	Fiber %	Carbohydrate %	Ash %	Energy (Kcal/100g)
T1	7.98	0.82	11.34	66.45	0.75	309
T2	8.23	0.81	11.25	66.70	0.83	315
T3	8.38	1.08	11.62	68.57	1.03	319
T4	8.74	1.08	11.62	68.57	1.03	319
T5	8.17	1.11	11.03	69.29	0.83	312
T6	8.43	0.84	11.35	67.96	0.76	312
T7	8.32	1.12	11.66	68.80	1.01	316
T8	8.55	1.12	11.66	68.80	1.09	320
T9	8.92	1.19	11.93	70.18	1.19	323
T10	8.43	1.13	11.35	67.44	0.76	316
T11	7.87	0.94	10.40	65.45	0.93	301
T12	8.00	0.96	10.45	66.18	0.95	318
T13	8.26	1.15	11.74	69.86	1.16	321
T14	7.42	1.01	11.19	66.33	1.00	301
Sem ±	0.11	0.03	0.17	0.58	0.03	2.38
CD (*p*=0.05)	0.31	0.09	0.49	0.69	0.08	6.92
CV (%)	2.22	5.45	2.58	1.48	5.2	1.31

Table 9. Economic analysis of the treatments

Treatments	Cost of cultivation (Rs.)	Gross return (Rs.)	Net return (Rs.)	B:C ratio
T1	68040	116536	48496	1.71
T2	67668	140423	72755	2.08
T3	67917	152046	84129	2.24
T4	68220	148707	80487	2.18
T5	66957	145203	78246	2.17
T6	67666	167479	99813	2.48
T7	68520	154367	85847	2.25
T8	66585	160087	93502	2.40
T9	67543	178557	111014	2.64
T10	68700	172773	104073	2.51
T11	65343	103797	38454	1.59
T12	66733	107305	40572	1.61
T13	68160	137751	69591	2.02
T14	41100	44520	3420	1.08

cytoplasm before reaching the endodermis and encountering the Casparian strip barrier (41).

Larger nanoparticles (generally 50-200 nm) primarily follow the apoplastic transport system, moving through non-living spaces including cell walls, intercellular gaps, middle lamella and xylem vessels. The movement along this pathway depends significantly on particle dimensions and electrical surface properties, which influence their interaction with plant tissues.

For systemic distribution throughout the maize plant, nanoparticles utilize the phloem transport network to move from treated leaves toward roots and other plant organs. The phloem sieve tubes, with their relatively large diameter capacity (accommodating particles up to approximately 0.405 μm), facilitate efficient long-distance transport of these nano-fertilizers (42). This uptake mechanism enables nano-N and P to be efficiently absorbed, distributed and utilized by maize plants, potentially enhancing nutrient delivery precision compared to conventional fertilizer applications.

The observed improvements in dry matter accumulation and nutrient uptake can be attributed to the unique characteristics of nano-fertilizers. The smaller particle size and increased surface area of nano-urea and nano-DAP facilitate enhanced nutrient solubility and cellular penetration, as supported by previous studies (43).

Nitrogen and phosphorus uptake

Notably, treatments incorporating nano-fertilizers (T8 and T9) demonstrated significantly higher nitrogen and phosphorus uptake compared to conventional fertilizer applications. The consistent performance across two consecutive growing seasons validates the reliability of nano-fertilizer applications. The temporal dynamics of nutrient uptake revealed interesting patterns, including a gradual decline in nitrogen content and relatively stable phosphorus retention, aligning with existing literature on nutrient remobilization in cereal crops. that multiple applications of nano-nitrogen at reduced rates promote sustained nutrient availability and translocation efficiency throughout the crop growth cycle. The declining trend in nitrogen content from 60 to 120 DAS observed across most treatments is consistent with normal plant physiological processes where nitrogen is remobilized from vegetative tissues to reproductive structures during later growth stages (44). Unlike nitrogen, phosphorus uptake showed relatively stable maintenance across growth stages in the high-performing nano fertilizer treatments. This stability could be attributed to the enhanced solubility, reduced fixation and sustained release characteristics of nano-phosphorus formulations (45, 46).

Nitrogen and phosphorus content in plant

The temporal dynamics reveal a general declining trend in nitrogen content across treatments from 60 to 120 DAS, consistent with normal plant physiological processes where nitrogen is diluted as biomass increases and remobilized from vegetative to reproductive structures during later growth stages. However, treatments T2, T8 and T9 maintained relatively higher nitrogen concentrations at 120 DAS (1.35 %, 1.32 % and 1.36 %) compared to other treatments, reflecting enhanced nutrient use efficiency.

Nano-phosphorus particles facilitate better penetration through plant cell membranes and maintain prolonged bioavailability, resulting in more stable tissue concentrations throughout the growing season (47). This differential performance could be attributed to the unique physicochemical properties of nano fertilizers that enhance cellular uptake, translocation and retention (48).

The agronomic efficiency analysis showed that nano fertilizer treatments could potentially reduce fertilizer inputs by up to 25 % while maintaining or even improving crop productivity. This finding is particularly significant in the context of sustainable agriculture, addressing critical challenges of resource optimization and environmental conservation (49).

The study contributes significantly to the emerging field of nanotechnology in agriculture, offering a scientifically robust approach to enhancing nutrient use efficiency and crop productivity while potentially mitigating the environmental footprint of traditional fertilization practices.

Conclusion

The study demonstrates that nano-fertilizers significantly enhance maize (*Zea mays* L.) nutrient utilization and agricultural productivity. By strategically integrating nano-nitrogen and nano-phosphorus fertilizers with reduced conventional fertilizer doses, the research demonstrated remarkable improvements in nutrient uptake efficiency, dry matter accumulation and agronomic performance. Specifically, treatment T9 achieved optimal performance with dry matter accumulation of 41.65 g/plant in leaves and 79.87 g/plant in stems, compared to 17.16 g/plant and 38.78 g/plant in control (T14). Nitrogen uptake reached 31.44 kg/ha and phosphorus uptake 5.60 kg/ha at 120 DAS, substantially higher than control values of 4.37 kg/ha and 1.43 kg/ha, respectively. Agronomic efficiency peaked at 67.9 % for nitrogen (T8) and 136 % for phosphorus (T12), demonstrating superior nutrient utilization. These findings establish nano-fertilizer integration as a promising strategy for sustainable agriculture with enhanced productivity and resource efficiency.

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Authors' contributions

BHR carried out the experiment, wrote draft paper and analysed the data. CK supported for data analysis and correction. HM, RHP and VVE supported for the final draft preparation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

AI declaration: ChatGPT tool was used for drawing conclusion (Chat GPT). After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Pal B, Jat SL. Enhancing state-wide corn (*Zea mays* L.) productivity by bridging the yield gap between top and average farmers in India. Maize J. 2024;13(2):1-5.
2. Ranum P, Peña-RosasJP, Garcia-Casal MN. Global maize production, utilization and consumption. Annals New York Acad Sci. 2014;1312(1):105-12. https://doi.org/10.1111/nyas.12396
3. Rajath HP, Kumar C, Hanumanthappa M, Bhanuprakash HR, Yogesh GS, Chandrakala H. Impact of weather parameters on maize agroecosystem and adaptation strategies under changing climatic conditions: A review on sustainable and climate-resilient adaptation strategies in maize agroecosystem. Plant Sci Today. 2023;10:1-10. https://doi.org/10.14719/pst.2164
4. IPCC. Climate change: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press; 2022.
5. Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, et al. Food security: The challenge of feeding 9 billion people. Science. 2010;327(5967):812-18. https://doi.org/10.1126/science.1185383
6. Balafoutis A, Beck B, Fountas S, Vangeyte J, Wal TVD, Soto I, et al. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability. 2017;9(8):1339. https://doi.org/10.3390/su9081339
7. Ciampitti IA, Vyn TJ. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crops Res. 2012;133:48-67. https://doi.org/10.1016/j.fcr.2012.03.008
8. Upadhyay PK, Singh VK, Rajanna GA, Dwivedi BS, Dey A, Singh RK, et al. Unveiling the combined effect of nano fertilizers and conventional fertilizers on crop productivity, profitability and soil well-being. Front Sustain Food Syst. 2023;7:1260178. https://doi.org/10.3389/fsufs.2023.1260178
9. Lassaletta L, Billen G, Grizzetti B, Anglade J, Garnier J. 50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland. Env Res Lett. 2014;9(10):105011. https://doi.org/10.1088/1748-9326/9/10/105011
10. Bhanuprakash HR, Sapkal DR, Hanumanthappa M, Rajath HP, Pandey S. Nanotechnology in agriculture for improving crop yield: A review. J Food Chem Nanotech. 2023;9(S1):S420-28. https://doi.org/10.17756/jfcn.2023-s1-053
11. Rameshaiah GN, Pallavi J, Shabnam S. Nano fertilizers and nano sensors – An attempt for developing smart agriculture. Int J Eng Res Gen Sci. 2018;3(1):314-20.
12. Sukbir K. Nano fertilizers: A new way to increase crop production. Int J Pharmaceu Sci Res. 2022;13(6):2299-2305.
13. Kah M, Tufenkji N, White JC. Nano-enabled strategies to enhance crop nutrition and protection. Nature Nanotech. 2018;14(6):532-40. https://doi.org/10.1038/s41565-019-0439-5
14. De Rosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nature Nanotech. 2010;5(2):91. https://doi.org/10.1038/nnano.2010.2
15. KarnyA, Zinger A, Kajal A, Shainsky-Roitman J, Schroeder A. Nanoparticles in plants: Mechanisms of uptake, translocation and seed transfer. Nanoscale. 2022;14(17):6420-35.
16. Tarafdar JC, Raliya R, Mahawar H, Rathore I. Development of zinc nanofertilizer to enhance crop production in pearl millet (*Pennisetum americanum*). Agric Res. 2014;3(3):257-62. https://doi.org/10.1007/s40003-014-0113-y
17. Adil M, Bashir S, Bashir S, Aslam Z, Ahmad N, Younas T, et al. Zinc oxide nanoparticles improved chlorophyll contents, physical parameters and wheat yield under salt stress. Front Plant Sci. 2022;13:932861.
18. Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustainable agriculture: Recent developments, challenges and perspectives. Front Microbiol. 2017;8:1014. https://doi.org/10.3389/fmicb.2017.01014
19. Worrall EA, Hamid A, Mody KT, Mitter N, Pappu HR. Nanotechnology for plant disease management. Agronomy. 2018;8(12):285. https://doi.org/10.3390/agronomy8120285
20. Lobell DB, Bänziger M, Magorokosho C, Vivek B. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Clim Change. 2011;1(1):42-45. https://doi.org/10.1038/nclimate1043
21. Payero JO, Melvin SR, Irmak S, Tarkalson D. Yield response of corn to deficit irrigation in a semiarid climate. Agric Water Manag. 2006;84(1-2):101-12. https://doi.org/10.1016/j.agwat.2006.01.009
22. Vetsch AJ, Randall GW. Corn production as affected by nitrogen application timing and tillage. Agron J. 2004;96(2):502-09. https://doi.org/10.2134/agronj2004.5020
23. Chhipa H. Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett. 2017;15(1):15-22. https://doi.org/10.1007/s10311-016-0600-4
24. Gomez KA, Gomez AA. Statistical procedures for Agricultural Research. 2nd edition. John Wiley & Sons, New York. 1984.
25. Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. Nano-fertilizers for balanced crop nutrition. In: Rai M, Ribeiro C, Mattoso L, Duran N, editors. Nanotechnologies in food and agriculture, Springer: Cham: 2015. p. 69–80. https://doi/10.1007/978-3-319-14024-7_3
26. Jackson ML. Soil chemical analysis, Prentice Hall, India, Pvt. Ltd., New Delhi. 1973.
27. Dimkpa CO, Bindraban PS. Nanofertilizers: New products for the agriculture industry. J Agric Food Chem. 2018;66(26):6462-73. https://doi.org/10.1021/acs.jafc.7b02150
28. Liu C, Wang Y, Pan K, Li W, Zhang L, Shen X. Responses of the dynamics of dry matter accumulation and distribution to nitrogen fertilizer in winter wheat. Agron J. 2019;111(4):1866-78.
29. Javed T, Indu I, Singhal RK, Shabbir R, Shah AN, Kumar P. Recent advances in agronomic and physio-molecular approaches for improving nitrogen use efficiency in crop plants. Front Plant Sci. 202213:877544. https://doi.org/10.3389/fpls.2022.877544
30. Zheng W, HE P, Gao Q, Sha ZM, Jin JY. Effect of N application on nitrogen absorption and utilization of spring maize under different soil fertilities. J Plant Nutr Fertil. 2011;17(2):301-09.
31. Holz M, Mundschenk E, Pusch V, Remus R, Dubbert M, Eva Oburger E, et al. Visualizing and quantifying ^{33}P uptake and translocation by maize plants grown in soil. Front Plant Sci. 2024;15:1376613. https://doi.org/10.3389/fpls.2024.1376613
32. Reddy VB, Reddy GP, Reddy MS. Effect of nutrient management and crop residue incorporation on phosphorus uptake of maize (*Zea mays* L.) at different growth stages. Int J Enviorn Clim Change. 2023;13(4):13-22. https://doi.org/10.9734/ijecc/2023/v13i41707
33. Zafar M, Abbasi MK, Arjumend T, Jabran K. Impact of compost, inorganic phosphorus fertilizers and their combination on maize growth, yield, nutrient uptake and soil properties. J Anim Plant Sci.

2012;22(4):1036-41.

34. Sharifi S, Shi S, Obaid H, Dong X, He X. Differential effects of nitrogen and phosphorus fertilization rates and fertilizer placement methods on P accumulations in maize. Plants. 2024;13(13):1778. https://doi.org/10.3390/plants13131778

35. Zhang D, Lyu Y, Li H, Tang X, Hu R, Rengel Z, et al. Neighbouring plants modify maize root foraging for phosphorus: Coupling nutrients and neighbours for improved nutrient‐use efficiency. New Phytol. 2020;226(1):244-53.

36. Irmak S, Mohammed AT. Maize nitrogen uptake and use efficiency, partial factor productivity of nitrogen and yield response to different nitrogen and water applications under three irrigation methods. Irrig Drain. 2024;73(1):64-88.

37. Gogoi B, Kanth RH, Bhat TA, Saxena A, Khan IM, Wani FJ. Efficacy of nano urea on nitrogen use efficiency of irrigated maize under temperate ecology. Arch Curr Res Int. 2024;24(6):396-409.

38. Easwaran C, Moorthy G, Christopher SR, Mohan P, Marimuthu R, Koothan V, et al. Nano hybrid fertilizers: A review on the state of the art in sustainable agriculture. Sci Total Environ. 2024;929:172533. https://doi.org/10.1016/j.scitotenv.2024.172533

39. Singh M, Goswami SP, Sachan P, Sahu DK, Beese S, Pandey SK. Nanotech for fertilizers and nutrients-improving nutrient use efficiency with nano-enabled fertilizers. J Exp Agric Int. 2024;46 (5):220-47.

40. Joseph M, Hemalatha M, Bhuvaneswari J, Srinivasan S, Leninraja D. Nano-fertilizers: The future of nutrient approaches for cereals. Indian J Agric Sci. 2024;94(11):1155-64.

41. Wang X, Xie H, Wang P, Yin H. Nanoparticles in plants: Uptake, transport and physiological activity in leaf and root. Materials. 2023;16(8):3097. https://doi.org/10.3390/ma16083097

42. Banerjee K, Pramanik P, Maity A, Joshi DC, Wani SH, Krishnan P. Methods of using nanomaterials to plant systems and their delivery to plants (mode of entry, uptake, translocation, accumulation, biotransformation and barriers)In: Ghorbanpour M, Wani SH, editors. Advances in phytonanotechnology. Academic Press; 2019.; p. 123-152. https://doi.org/10.1016/B978-0-12-815322-2.00005-5

43. Kekeli MA, Wang Q, Rui Y. The role of nano-fertilizers in sustainable agriculture: Boosting crop yields and enhancing quality. Plants. 2025;14(4):554.

44. Rathwa MK, Bhanvadia AS. Impact of irrigation scheduling and nitrogen management through drip irrigation system on nutrient content and uptake of rabi maize (*Zea mays* L.). Int J Plant Soil Sci. 2023;35(23):345-55. https://doi.org/10.9734/ijpss/2023/v35i234249

45. Sairam M, Maitra S, Sahoo U, Sagar LT, Krishna G. Evaluation of precision nutrient tools and nutrient optimization in maize (*Zea mays* L.) for enhancement of growth, productivity and nutrient use efficiency. Res Crops. 2023;24(4):666-77. https://doi.org/10.31830/2348-7542.2023.roc-1016

46. Rimmi, Naznin S, Islam MS, Alam MS, Rahman Khan MA, Binte BI. Response of irrigation and nitrogen fertilization on uptake of primary nutrients by maize. Asian J Adv Agric Res. 2023;23(3):89-87. htttps://doi.org/10.9734/ajaar/2023/v23i3471

47. Kumar KN, Mani A, Babu GR, Rao CH. Spatial and temporal distribution of nitrogen in maize under drip fertigation. Int J Plant Soil Sci. 2024;36(5):375-92.

48. Begam A, Pramanick M, Dutta S, Paramanik B, Dutta G, Patra PS, et al. Inter-cropping patterns and nutrient management effects on maize growth, yield and quality. Field Crops Res. 2024;310:109363.

49. Kumar Y, Singh T, Raliya R, Tiwari KN. Nano fertilizers for sustainable crop production, higher nutrient use efficiency and enhanced profitability. Indian J of Fert. 2021;17(11):1206-14.

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