PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(4): 1000-1011
https://doi.org/10.14719/pst.4380

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RESEARCH ARTICLE

Nutrient and energy conservation through nano-fertilizers in maize

Asha Kiran K[1], Jayadeva HM[1], Vinay M Gangana Gowdra[1*], Pruthviraj N[2], Kotresh DJ[1] & Devika AR[3]

[1]Department of Agronomy, University of Agricultural Sciences, Gandhi Krishi Vigyana Kendra, Bengaluru 560 065, India

[2]Centre of Excellence on Watershed Management, University of Agricultural Sciences, Gandhi Krishi Vigyana Kendra, Bengaluru 560 065, India

[3]Department of Agronomy, Indian Agriculture Research Institute, New Delhi 110 012, India

*Email: vinaymg.581@gmail.com

OPEN ACCESS

ARTICLE HISTORY
Received: 18 July 2024
Accepted: 16 September 2024
Available online
Version 1.0 : 31 October 2024
Version 2.0 : 31 October 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE
Asha KK, Jayadeva HM, Gangana Gowdra VM, Pruthviraj N, Kotresh DJ, Devika AR. Nutrient and energy conservation through nano-fertilizers in maize. Plant Science Today. 2024; 11(4): 1000-1011. https://doi.org/10.14719/pst.4380

Abstract

In the current scenario, achieving food security while conserving resources and energy is a significant challenge. Maize is a widely cultivated but nutrient-exhaustive crop. The adoption of nanotechnology-based nano-fertilizers offers a pathway for achieving sustainable yields while reducing fertilizer requirements and conserving energy. A field experiment was conducted during the Kharif season of 2021 to explore nutrient and energy conservation through nano-fertilizers in maize at the University of Agricultural Sciences, GKVK, Bengaluru. The experiment involved nine treatments comprising various combinations of the recommended dose of fertilizers (RDF) with nano-urea and nano di-ammonium phosphate (DAP) under a randomized complete block design (RCBD). The results indicated that Treatment T5 - 75% of the recommended dose of nitrogen (RDN) + nano-N-achieved a higher yield (10.20% higher than the conventional practice, T1-RDF + farmyard manure (FYM)) and improved nutrient uptake at harvest [299.22, 55.56 and 208.26 kg of nitrogen (N), phosphorus (P), and potassium (K) per hectare, respectively]. This treatment also demonstrated greater physiological efficiency (36.11, 200.66 and 52.70 kg of maize per kg of N, P and K, respectively), higher energy output (260,851 MJ ha^{-1}), improved energy use efficiency (16.93), enhanced energy productivity (0.627 kg MJ^{-1}), and better energy profitability (15.93). Using 75% of RDN + nano-N increases yield while reducing fertilizer use and conserving energy.

Keywords

agronomic efficiency; energy utilization; nano DAP; nano urea

Introduction

Maize (*Zea mays* L.) belongs to the Poaceae family and is popularly known as the "Queen of Cereals" due to its wider adaptability and higher production potential. After wheat and rice, it is the third most important cereal crop in India (1). India ranks fourth in terms of cultivated area and seventh in maize production. Maize is nutritionally rich containing 72% starch, 10% protein, 8.5% fiber, 4.8% oil, 3.0% sugar and 1.7% ash (2). In addition to being a key staple food and fodder crop, maize is also used to produce gluten, starch and cooking oil.

Maize is a nutrient-intensive crop that requires high nutrient levels to achieve the yields necessary to meet the growing population's food demands. Nutrient management plays a crucial role in determining crop yield. Since the

Green Revolution, farmers have relied heavily on conventional inorganic fertilizers to meet crop nutrient requirements and achieve satisfactory yields. However, the excessive use of chemical fertilizers, while boosting crop production, has degraded the soil's physiochemical properties and harmed its microbial population (3). Conventional fertilizers are also prone to losses through leaching, fixation, immobilization, runoff and volatilization. The overuse of N and P fertilizers has become a significant anthropogenic factor contributing to eutrophication in lakes, rivers and other freshwater bodies worldwide (4). With changing global climatic conditions and increasing energy demands, there is a need for advanced technologies that enhance nutrient use efficiency and produce higher output with less energy. To address these challenges, researchers have developed nanotechnology-based nano-fertilizers, which can complement conventional fertilizers. This innovative approach reduces energy consumption during production and improves nutrient use efficiency by minimizing the losses associated with traditional fertilizers.

Among essential nutrients, N is the most critical element, serving as an integral component of nucleic acids, amino acids, phytohormones and chlorophyll. It is also the primary nutrient most deficient in Indian soils (3). Phosphorus is another vital nutrient, playing a key role in the structure of cell membranes, ATP and nucleic acids, while also being essential for protein activation and energy transfer processes (5). Farmers commonly use urea, DAP, and single super phosphate (SSP) to meet the N and P requirements of crops, though these fertilizers often have limited efficiency. Therefore, the present study was conducted to examine the effects of nano-fertilizers (nano-N and nano-NP) on maize yield, nutrient uptake, nutrient use efficiency and energy dynamics.

Materials and Methods

Study site

The experiment was conducted during the Kharif season of 2021 at the Zonal Agricultural Research Station (ZARS), Gandhi Krishi Vignana Kendra (GKVK), University of Agricultural Sciences, Bangalore. The research station is located at 13° 05' N latitude, 77° 34' E longitude, and at an altitude of 924 meters above mean sea level, falling under the Eastern Dry Zone (ACZ-V) of Karnataka. The station received an actual annual rainfall of 1328.4 mm, with the majority occurring between June and November. October and November recorded the highest rainfall, with 231.6 mm and 367.4 mm, respectively. An initial soil analysis of the experimental site (Table 1) indicated that the soil was red sandy loam in texture, as determined by the international pipette method (6). The soil was moderately acidic, with normal electrical conductivity and medium levels of available N, P and K.

Experimental design and crop management

The field experiment was laid out in a RCBD with nine treatments replicated thrice, and the maize cultivar used was BRMH-8. The treatment details are as follows:

T_1: RDF with FYM

T_2: RDF

T_3: 25% RDN + nano-N

T_4: 50% RDN + nano-N

T_5: 75% RDN + nano-N

T_6: 25% RDNP + nano-NP

T_7: 50% RDNP + nano-NP

T_8: 75% RDNP + nano-NP

T_9: Absolute control

Note:

RDF: 150:75:40 kg N:P:K ha^{-1}, FYM: 10 t ha^{-1}

RDN: Recommended dose of nitrogen through conventional fertilizer.

RDNP: Recommended dose of nitrogen and phosphorus through conventional fertilizer.

Nano-N: nano nitrogen

Nano-NP: nano nitrogen and phosphorus

Nutrients were applied according to the treatment plan using urea, SSP, and muriate of potash (MOP) to supply N, P and K, respectively. The RDN was applied in three splits, and sowing was carried out with a spacing of 60 cm × 30 cm after preparing the soil to a fine tilth. Irrigations were provided based on crop requirements, considering rainfall and soil moisture content. A foliar spray of nano-N (2 ml L^{-1}) and nano-NP (1.25 ml L^{-1}) was applied at 30 and 60 DAS, as per the treatments. The source of nano-N particles was Indian Farmers Fertiliser Cooperative Limited (IFFCO) nano-Urea (liquid), and the source of nano-NP particles was IFFCO nano-DAP (liquid), both obtained from the IFFC.

Observations

The grain and stover yield obtained from the net plot area was converted and expressed in kg ha^{-1}.

Soil analysis

Representative soil samples from the experimental plots were collected from the top 0-15 cm depth both before sowing and after harvesting the crop. The methods used for soil analysis and the initial physicochemical properties of the soil prior to cultivation are provided in Table 1.

Collection of plant samples

Plant samples were collected before the application of nano-N and nano-NP at 30 and 60 DAS. Additionally, plant samples were taken seven days after the spraying of nano-fertilizers and at harvest. The collected plant samples were cleaned, shade-dried, and then dried in an oven at 65 °C. After drying, the samples were powdered and stored for chemical analysis (7).

Plant analysis

Nitrogen content was estimated using the modified Micro-Kjeldahl method (VELP Scientifica UDK 159 automatic distillation and titration system) and expressed as a percentage (8). For the estimation of P and K, a one-gram plant sample was digested with a di-acid mixture of nitric

Table 1. Initial Physico-chemical properties of soil of the experimental site

Particulars	Values	Methods followed
Coarse sand (%)	53.4	International pipette method (6)
Fine sand (%)	14.8	
Silt (%)	16.6	
Clay (%)	15.2	
pH (1:5)	5.61	Potentiometric method, pH meter (10)
EC (dS m^{-1})	0.189	Conductometry (10)
Available N (kg ha^{-1})	441.18	Alkaline permanganate method (8)
Available P_2O_5 (kg ha^{-1})	36.25	Brays method (10)
Available K_2O (kg ha^{-1})	280.62	Neutral normal ammonium acetate method (10)

acid (HNO_3, 65%) and perchloric acid ($HClO_4$, 70%) in a 9:4 ratio of HNO_3 to $HClO_4$ (9). The filtered digested material was diluted to a final volume of 50 ml with 6 N hydrochloric acid (HCl, 37%) for analysis. Phosphorus content in the digested plant sample was estimated using the vanadomolybdophosphoric acid yellow colour method in a nitric acid medium, with colour intensity measured at 660 nm using a spectrophotometer (Visible Spectrophotometer 168) (10). Potassium content in the plant sample digest was measured by atomizing the diluted acid extract in a flame photometer (Systronics Flame Photometer 128) (10). Nutrient uptake was calculated using the following formulas (11).

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

(Eqn.1)

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

(Eqn.2)

$$\text{Potassium uptake (kg ha}^{-1}) = \frac{\text{Potassium content (\%)}}{100} \times \text{Dry matter (kg ha}^{-1})$$

(Eqn.3)

Nutrient use efficiency (NUE)

The amount of products produced per unit of resource used is referred to as nutrient use efficiency. Different nutrient use efficiency that were calculated is given below

Agronomic efficiency is the economic production obtained per unit of nutrient applied (12). It can be calculated with the help of the following equation and expressed as kg kg^{-1}

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

(Eqn.4)

Physiological efficiency (PE) indicates an increase in grain yield (kg) per unit of nutrient uptake (kg) from the application of fertilizer (13) and expressed as kg kg^{-1}

$$\text{PE (kg kg}^{-1}) = \frac{\text{Grain yield of fertilized plot – Grain yield of control plot}}{\text{Nutrient uptake of fertilized plot – Nutrient uptake of control plot}}$$

(Eqn.5)

Apparent recovery efficiency is the quantity of nutrients taken up by the crop per unit of nutrient applied (13) and expressed as a percentage.

$$\text{ARE (kg kg}^{-1}) = \frac{\text{Nutrient uptake of the fertilized plot – Nutrient uptake of the control plot}}{\text{Quantity of nutrient applied (kg)}}$$

(Eqn.6)

Energetics

The energy equivalent of input and output used for the energy balance determination (14-25) is depicted in Table 2. Energy analysis was done using the following formulae (26).

$$\text{Net energy (MJ ha}^{-1}) = \text{Energy output (MJ ha}^{-1}) - \text{Energy input (MJ ha}^{-1})$$

(Eqn.7)

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ ha}^{-1})}{\text{Energy input (MJ ha}^{-1})} \quad \text{(Eqn.8)}$$

$$\text{Energy productivity} = \frac{\text{Kernel yield (Kg ha}^{-1})}{\text{Energy input (MJ ha}^{-1})} \quad \text{(Eqn.9)}$$

$$\text{Energy profitability} = \frac{\text{Net energy (MJ ha}^{-1})}{\text{Energy input (MJ ha}^{-1})} \quad \text{(Eqn.10)}$$

Statistical analysis

The experimental data collected were analyzed using Fisher's method of analysis of variance (ANOVA) (27). All data were evaluated and the results were presented and discussed at a significance level of 5%.

Results

Influence of nano fertilizers on maize kernel and stover yield

The effect of nano-fertilizers on the kernel and stover yield of maize yielded significant results (Fig. 1). The application of 75% RDN + nano-N (T5) resulted in significantly higher kernel and stover yields of 9,654 kg ha^{-1} and 9,515 kg ha^{-1}, respectively, which represent increases of 10.20% and 9.29% compared to RDF + FYM (T1), following the recommended package of practices. This yield was comparable to that of T8 (75% RDNP + nano-NP), which produced 9,134 kg ha^{-1} of kernel yield and 9,046 kg ha^{-1} of stover yield. In contrast, the lowest yields were observed in T9 (absolute control), with 3,737 kg ha^{-1} for kernels and 4,773 kg ha^{-1} for stover.

Table 2. Energy equivalents (MJ unit^{-1}) used for energy calculations

Sl. No.	Particulars	Energy equivalent (MJ unit^{-1})	References
I		Input	
1.	Human labour (hr)	1.96	(14-16)
2.	Machinery (hr)	62.7	(17, 18)
3.	Diesel fuel (L)	56.31	(14, 17)
4.	Farmyard manure (kg)	0.3	(19)
5.	Chemical fertilizers (kg)		
	a. Nitrogen	60.6	(17, 20)
	b. Phosphorus	11.1	(17, 20)
	c. Potassium	6.7	(17, 20)
6.	Chemicals (kg)		
	a. Herbicide	102	(21, 22)
	b. Insecticide	102.2	(21, 23)
7.	Seed (kg)	14.7	(20)
8.	Irrigation (m^3)	1.02	(18, 24)
9.	Electricity (kWh)	11.93	(15)
II		Output	
1.	Grain (kg)	14.7	(14, 25)
2.	Stover (kg)	12.5	(14, 25)

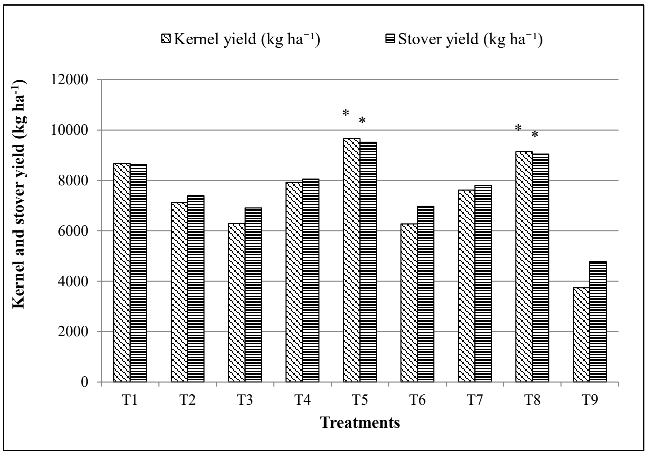


Fig. 1. Effect of nano fertilizers on maize kernel and stover yield.

Influence of nano fertilizers on nutrient uptake by maize

Nitrogen and phosphorus uptake by maize at 30 and 60 days after sowing (DAS)

The impact of nano-N and nano-NP on maize was assessed by examining N and P uptake before and seven days after the application of nano-fertilizers at 30 and 60 DAS. The N and P uptake data at these intervals are presented in box and whisker plots in Fig. 2 to 5.

Nitrogen uptake at 30 DAS (Fig. 2A), prior to the application of nano-fertilizers, was highest in T1 (RDF + FYM), with an uptake of 11.6 kg N ha^{-1}. This was comparable to T2 (RDF), which had an uptake of 10.6 kg N ha^{-1} and T5 (75% RDN + nano-N), with 10.1 kg N ha^{-1}. Seven days after the application of nano-fertilizers (Fig. 2B), T5 (75% RDN + nano-N) recorded significantly higher N uptake with 16.3 kg N ha^{-1}, representing an increase of 20.9% over the conventional fertilizer treatment T1 (RDF + FYM). This uptake was comparable to that of T8 (75% RDNP + nano-NP)**,** which recorded 15.2 kg N ha^{-1}.

Similarly, P uptake before the application of nano-fertilizers at 30 DAS (Fig. 3A) was highest in T1 (RDF + FYM), with an uptake of 2.19 kg P ha^{-1}, which was similar to T2 (RDF) at 2.03 kg P ha^{-1} and T5 (75% RDN + nano-N) at 1.99 kg P ha^{-1}. Seven days after the application of nano-fertilizers (Fig. 3B), 75% RDN + nano-N recorded higher P uptake of 4.15 kg P ha^{-1}, showing an increase of 22% over the conventional fertilizer treatment and comparable to T8 (75% RDNP + nano-NP), which had 4.12 kg P ha^{-1}. In contrast, significantly lower N and P uptake were observed in T9 (absolute control), with 3.6 kg N ha^{-1} and 0.99 kg P ha^{-1}, respectively.

At 60 DAS, the data collected before and seven days after the application of nano-fertilizers followed a similar trend to that observed at 30 DAS. The results indicated that significantly higher N and P uptake before the application (Fig. 4A and 5A) was recorded in T5 (75% RDN + nano-N), with uptake values of 69.1 kg N ha^{-1} and 14.48 kg P ha^{-1}, respectively. These values were comparable to those of T8

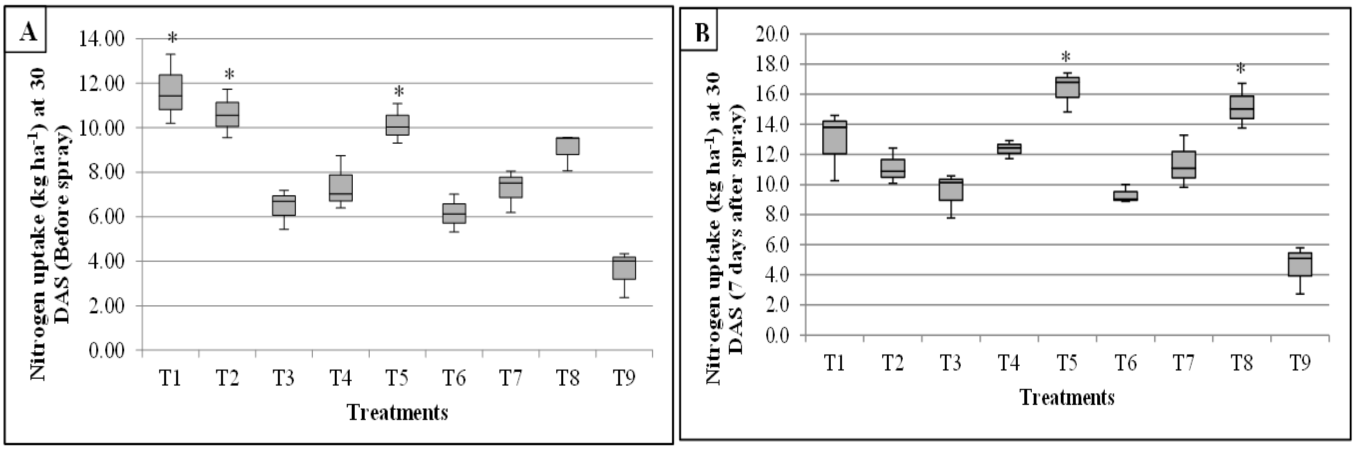


Fig. 2. Effect of nano fertilizers on nitrogen uptake (kg ha^{-1}) at 30 DAS (A) before spray (B) 7 days after spray.

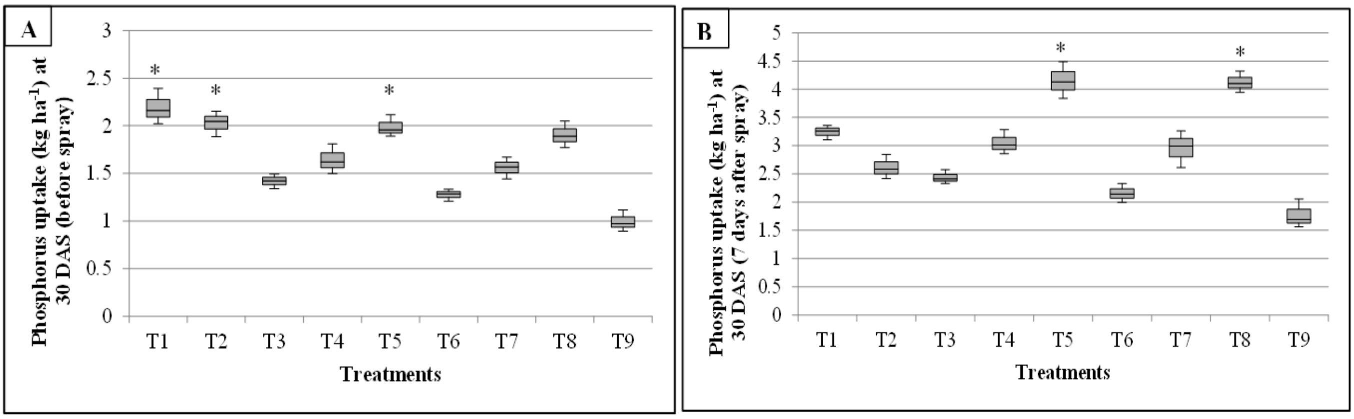


Fig. 3. Effect of nano fertilizers on phosphorus uptake (kg ha^{-1}) at 30 DAS (A) before spray (B) 7 days after spray.

(75% RDNP + nano-NP), which recorded 63.1 kg N ha^{-1} and 13.78 kg P ha^{-1}. In contrast, significantly lower nutrient uptake was observed in T9 (absolute control), with values of 38.6 kg N ha^{-1} and 5.78 kg P ha^{-1}, respectively. Furthermore, seven days after the application of nano-fertilizers (Fig. 4B and 5B), T5 (75% RDN + nano-N) also exhibited significantly higher N and P uptake, with values of 75.1 kg N ha^{-1} and 16.72 kg P ha^{-1}, respectively. This was comparable to T8 (75% RDNP + nano-NP), which showed 70.7 kg N ha^{-1} and 15.90 kg P ha^{-1}.

Nitrogen, phosphorus and potassium uptake by maize at harvest stage

The application of nano-fertilizers significantly influenced nutrient uptake by the crop at the harvest stage (Fig. 6). The 75% RDN + nano-N (T5) treatment recorded significantly higher N uptake in stover, grain and total N uptake by the crop, with values of 121.34 kg ha^{-1}, 177.88 kg ha^{-1} and 299.22 kg ha^{-1}, respectively. This was followed closely by T8 (75% RDNP + nano-NP), which showed N uptake values of 119.46 kg ha^{-1}, 176.87 kg ha^{-1} and 296.34 kg ha^{-1} for stover, grain and total uptake, respectively. In contrast, significantly lower N uptake was observed in T9 (absolute control), with values of 61.27 kg ha^{-1}, 74.09 kg ha^{-1} and 135.36 kg ha^{-1} for stover, grain and total uptake, respectively.

A comparable tendency was noted regarding the absorption of P and K by the crop during the harvest stage (Fig. 7 and 8). The application of 75% RDN + nano-N (T5) resulted in significantly higher P (22.92, 32.64 and 55.56 kg ha^{-1}) and K (110.37, 97.89 and 208.26 kg ha^{-1}, respectively) in stover, grain and total uptake by the maize crop. This treatment was found to be on par with 75% RDNP + nano-NP (T8), which recorded 22.82, 32.32 and 54.14 kg ha^{-1} of P and 105.30, 94.85 and 200.15 kg ha^{-1} of K in stover, grain and total uptake by the maize. The significantly lower accumulation of P (10.51, 15.07 and 25.58 kg ha^{-1}) and K (55.05, 40.01 and 95.06 kg ha^{-1}) in stover, grain and total uptake was recorded in the absolute control (T9).

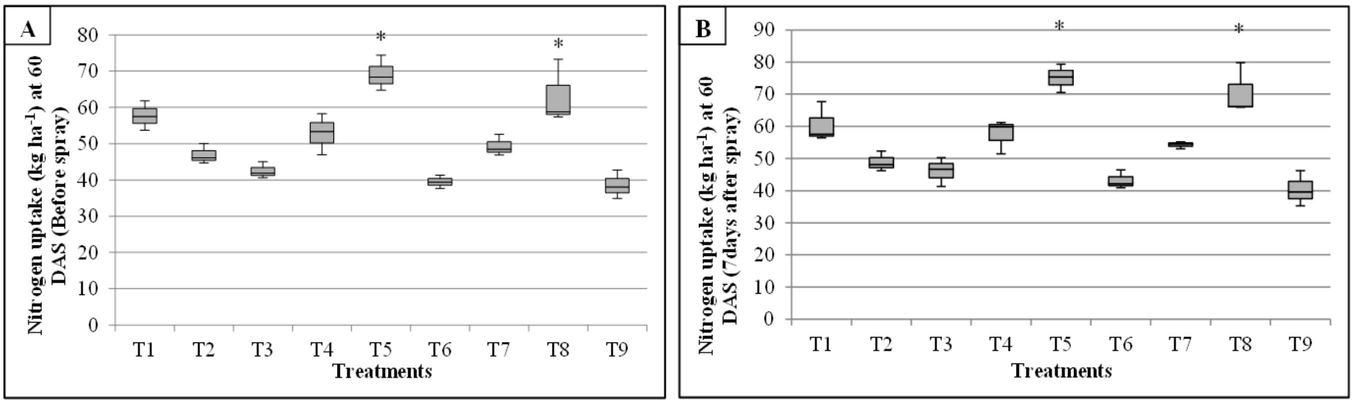


Fig. 4. Effect of nano fertilizers on nitrogen uptake (kg ha^{-1}) at 60 DAS (A) before spray (B) 7 days after spray.

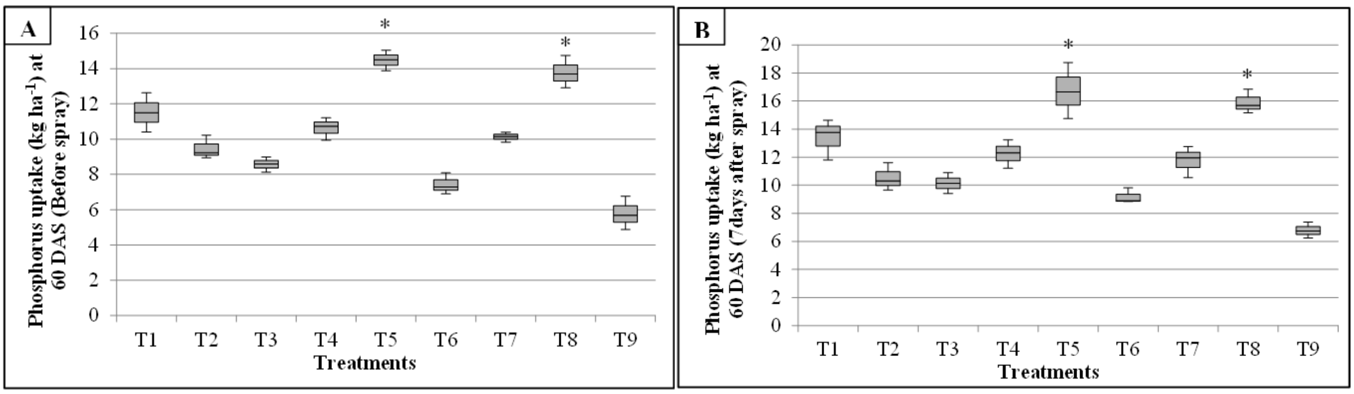


Fig. 5. Effect of nano fertilizers on phosphorus uptake (kg ha^{-1}) at 60 DAS (A) before spray (b) 7 days after spray.

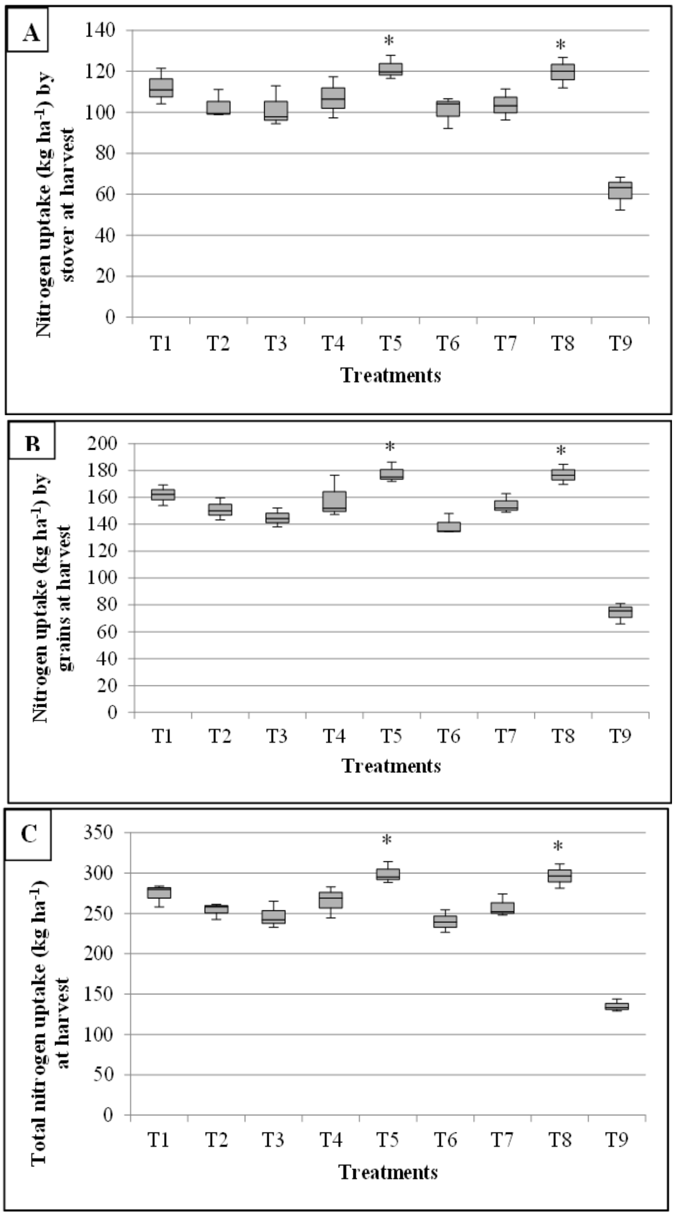


Fig. 6. Effect of nano fertilizers on nitrogen uptake (kg ha^{-1}) at harvest by (A) Stover, (B) Grains and (C) Total.

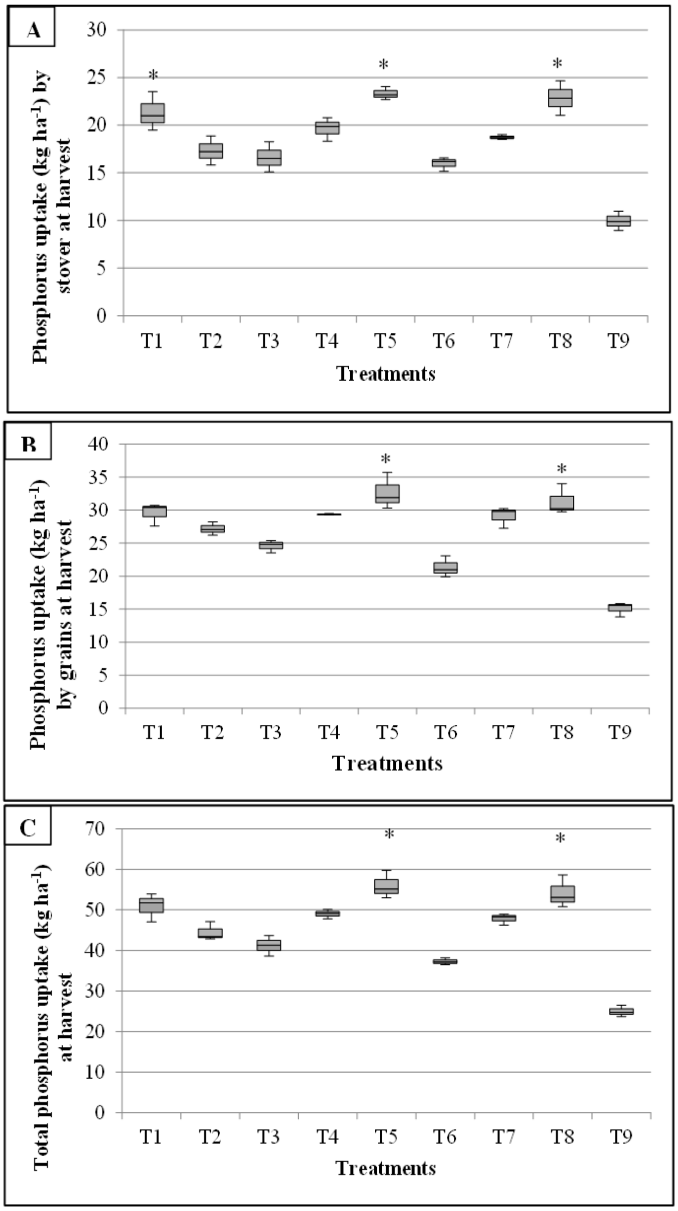
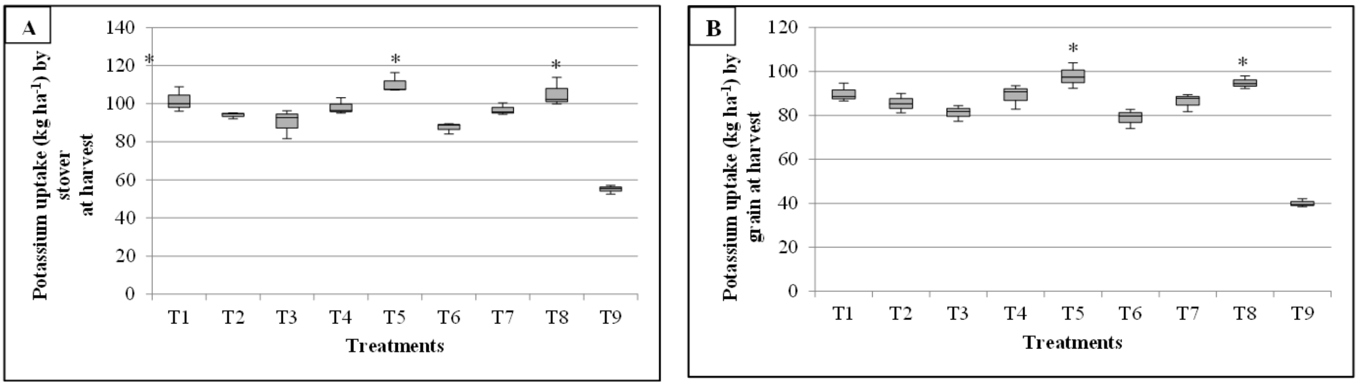


Fig. 7. Effect of nano fertilizers on phosphorus uptake (kg ha^{-1}) at harvest by (A) Stover, (B) Grains and (C) Total.



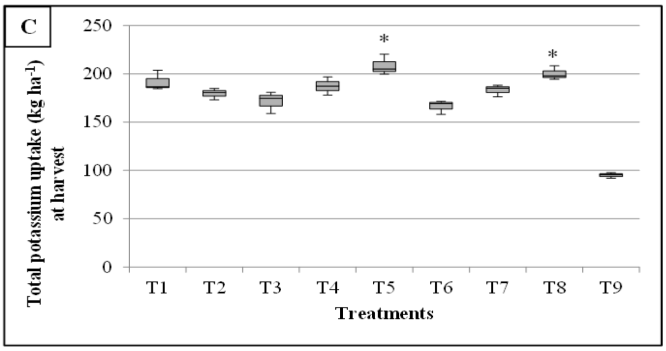


Fig. 8. Effect of nano fertilizers on potassium uptake (kg ha^{-1}) at harvest by (A) Stover, (B) Grains and (C) Total.

Influence of nano-fertilizers on nutrient use efficiency of maize

Influence of nano-fertilizers on agronomic efficiency (AE), physiological efficiency (PE) and apparent recovery efficiency (ARE) of maize

The impact of nano fertilizers on AE, physiological efficiency (PE) and ARE of N, P and K was found to be significant (Table 3). A significantly higher AE_N was observed in T3, which involved the application of 25% RDN + nano-N (68.09 kg kg^{-1}), and this was found to be on par with T6 (25% RDNP + nano-NP), which recorded 67.32 kg kg^{-1}. AE_P was significantly higher in T6 with the application of 25% RDNP + nano-NP (132.99 kg kg^{-1}). In contrast, T5 (75% RDN + nano-N) recorded significantly higher AE_K (147.93 kg kg^{-1}). Regarding physiological efficiency (PE), the application of 75% RDN + nano-N (T5) recorded significantly higher PE_N, which was on par with RDF + FYM (T1) and 75% RDNP + nano-NP (T8). PE_P showed significantly higher results with the 25% RDNP + nano-NP treatment (T6), which was comparable to 75% RDN + nano-N (T5). Meanwhile, significantly higher PE_K was observed in the 75% RDN + nano-N (T5) application, followed by the 75% RDNP + nano-NP (T8) and RDF with FYM (T1) applications. The apparent recovery efficiency of N, i.e., ARE_N, was recorded with the application of T3 (25% RDN + nano-N) at 295.42%, and the application of T6 (25% RDNP + nano-NP) was found to be significantly on par with ARE_N at 277.75%. ARE_P was significantly higher with the application of T6 (25% RDNP + nano-NP) at 60.91%, which was on par with T7 (50% RDNP + nano-NP) at 58.47%. Additionally, significantly higher ARE_K was recorded in T5 (75% RDN + nano-N) treatment (283.02%), which was on par with T8 (75% RDNP + nano-NP) at 262.74%.

Influence of nano-fertilizers on energy usage in maize

Consuming less energy while yielding higher output energy will be considered an efficient production system. Supplementing conventional fertilizers with nano fertilizers is one tool to reduce input energy and increase output energy. Therefore, energy budgeting was conducted to determine the extent of energy savings involved in maize production by including nano fertilizers, as depicted in Table 4. The input energy involved in the present study varied from 7,478 to 20,669 MJ ha^{-1}, with the highest energy input observed in RDF + FYM (T1). In contrast, energy output and net energy were significantly higher in T5, with the application of 75% RDN + nano-N (260,841 and 245,447 MJ ha^{-1}, respectively). This was significantly comparable to T8, with the application of 75% RDNP + nano-NP (247,347 and 231,429 MJ ha^{-1}, respectively). In the same treatment, T5 recorded significantly higher energy use efficiency, energy productivity and energy profitability (16.93, 0.627 kg MJ^{-1}, and 15.93, respectively), followed by T4 (50% RDN + nano-N) with values of 16.53, 0.603 kg MJ^{-1} and 15.53, respectively, and T3 (25% RDN + nano-N) with values of 16.48, 0.580 kg MJ^{-1} and 15.48, respectively.

Soil available nutrients after harvest of maize crop

The effect of the present study on maize significantly altered the soil's available nutrient status after harvest, as depicted in Table 5. The higher available soil N (315.8 kg ha^{-1}), P (42.4 kg ha^{-1}), and K (135.5 kg ha^{-1}) were recorded in FYM + RDF (T1) treatment. Available N showed significantly on-par results with RDF application (298.6 kg ha^{-1}), whereas available P was found on par with T3-25% RDN + nano-N (37.4 kg ha^{-1}) and T4-RDF application (36.9 kg ha^{-1}). The available soil K showed on par with T6-25% RDNP + nano-NP (126.3 kg ha^{-1}) and T3-25% RDN + nano-N application (117.5 kg ha^{-1}). This might be due to the application of higher fertilizers to the soil and the residual effect of FYM.

Discussion

Maize kernel and stover yield

The higher kernel and stover yields in maize with the application of 75% RDN + nano-N (T5) are mainly

Table 3. Effect of nano fertilizers on different nutrient use efficiency in maize

Treatments	Agronomic efficiency (kg kg^{-1})			Physiological efficiency (kg kg^{-1})			Apparent recovery efficiency (%)		
	AE_N	AE_P	AE_K	PE_N	PE_P	PE_K	ARE_N	ARE_P	ARE_K
T_1	25.96	53.04	63.24	35.81	195.37	51.36	72.92	27.31	123.85
T_2	22.51	45.01	84.40	28.62	171.58	40.92	79.14	26.54	211.09
T_3	68.09	34.16	64.04	23.25	165.62	34.3	295.42	20.79	191.05
T_4	55.72	55.81	104.65	32.58	178.04	45.44	173.24	31.63	230.66
T_5	52.54	78.90	147.93	36.11	200.66	52.70	145.46	39.97	283.02
T_6	67.32	132.99	63.36	24.4	219.10	35.81	277.75	60.91	177.98
T_7	51.6	102.52	96.90	31.82	175.75	44.04	163.36	58.47	220.32
T_8	47.97	95.43	134.93	33.55	189.18	51.40	160.09	50.49	262.74
T_9	-	-	-	-	-	-	-	-	-
F-test	*	*	*	*	*	*	*	*	*
S.Em ±	3.79	5.12	7.86	1.01	7.14	1.64	15.91	2.64	8.18
CD (p=0.05)	11.37	15.34	23.57	3.02	21.4	4.92	47.69	7.91	24.51

Note: CD - critical difference; S. Em - standard error of mean; F test - fishers LSD test at 5% significance; AE – agronomic efficiency; PE – physiological efficiency; ARE – apparent recovery efficiency; N – nitrogen; P – phosphorus; K - potassium

Table 4. Effect of nano fertilizers on energetics in maize

Treatments	Energy input (MJ ha^{-1})	Energy output (MJ ha^{-1})	Net energy (MJ ha^{-1})	Energy use efficiency	Energy productivity	Energy profitability
T_1	20669	235325	214656	11.39	0.419	10.39
T_2	17669	196939	179270	11.15	0.403	10.15
T_3	10859	178946	168087	16.48	0.580	15.48
T_4	13131	217110	203979	16.53	0.603	15.53
T_5	15404	260851	245447	16.93	0.627	15.93
T_6	11111	179363	168252	16.14	0.564	15.14
T_7	13437	209404	195967	15.58	0.567	14.58
T_8	15918	247347	231429	15.54	0.574	14.54
T_9	7478	114596	107117	15.32	0.500	14.32
F-test	-	*	*	*	*	*
S.Em ±	-	6474	6474	0.404	0.021	0.40
CD (p=0.05)	-	19410	19410	1.210	0.062	1.21

Note: CD - critical difference; S. Em - standard error of the mean; F test - fishers LSD test at 5% significance

Table 5. Effect of nano fertilizers on available soil nutrients status after harvest of maize

Treatments	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
T_1	315.8	42.4	135.5
T_2	298.6	36.9	106.8
T_3	237.4	37.4	117.5
T_4	234.0	25.2	105.6
T_5	227.6	24.5	89.8
T_6	240.0	11.7	126.3
T_7	235.3	14.5	109.7
T_8	230.5	18.3	99.6
T_9	218.3	9.8	81.9
F-test	*	*	*
S.Em ±	9.95	2.46	7.83
CD (p=0.05)	29.82	7.37	23.47

Note: CD - critical difference; S. Em - standard error of the mean; F test - fishers LSD test at 5% significance

attributable to the synergistic effect of conventional soil-applied urea and foliar-applied nano N, which enhanced the uptake of N at critical crop growth stages (28). Nitrogen is an important component of many amino acids, such as glutamic acid and glycine, which are fundamental metabolites in the formation of chlorophyll and vegetative tissue. This enhancement leads to a higher degree of photosynthesis, which in turn increases total dry matter accumulation in plants (29). The greater leaf area and prolonged senescence of leaves contributed to increased dry matter production and the translocation of photosynthates from source to sink. This improved source-to-sink relationship results in higher yield attributes, leading to increased kernel and stover yields. It has also been reported that applying nano N at 4 ml L^{-1}, along with 75% RDN + RDPK, recorded significantly higher grain yields in maize (30). Similar findings have been observed with the nano application of NPK in rabi maize (31) and nano urea in rice (32).

Influence of nano fertilizers on nutrient uptake by maize

Nitrogen and phosphorus uptake by maize at 30 and 60 days after sowing (DAS)

The higher N and P uptake in 75% RDN + nano-N (T5) after the spray of nano fertilizer at 30 and 60 DAS was mainly due to the combined effect of split application of N to the soil and the direct supply of N to the target site (leaf) through foliar spray in nano form. This form can easily penetrate the leaves through the pores on the leaf surface, such as stomata and hydathodes, making N readily available for plant growth (33). Additionally, the smaller size and controlled release of nanoparticles prevent the nutrient ions from either becoming fixed or being lost to the environment, thereby increasing nutrient availability for plant uptake (34, 35). In contrast, conventional urea application may have led to N loss through leaching and volatilization, resulting in lower N availability to the plants and consequently, lower N uptake compared to the nano-N treatment. Higher N uptake at the tasseling stage in maize was observed when 4% POCU (pine oleoresin-coated urea) was applied due to its slow-release nature of N compared to conventional urea (36).

Nitrogen, phosphorus and potassium uptake by maize at the harvest stage

The higher N uptake observed in the 75% RDN + nano-N (T5) treatment may be attributed to the replacement of

25% of the conventional urea source with a nano form of N, which has a size of less than 5 nm and a greater absorptive surface area, making it more available for various metabolic activities. Similar results were found in rice, where the application of 100% NPK + nano N at the active tillering stage was more impactful and resulted in significantly higher N uptake at harvest (28). Applying only conventional urea to meet the N requirements of maize can lead to various losses (leaching, volatilization, and runoff), which can be mitigated by supplementing part of it with nano N, resulting in higher N uptake. These findings align with results observed in pearl millet (37). The nano form of N can easily penetrate the pores of leaves and later reach different parts of the plants, triggering metabolic activity, which further increases acidity and the exudation process in the roots of plants (38). This root exudation may facilitate the dissolution of fixed forms of P in the soil, making it more available to the plants and ultimately leading to increased P uptake. Applying 75% of RDN and two foliar sprays of nano urea at the active tillering and panicle initiation stages in rice recorded higher P uptake of 16.10 and 11.24 kg ha^{-1} by grain and straw, respectively (39). Similar results were observed with the application of 4 ml L^{-1} of nano urea at 30 and 45 DAS, along with conventional fertilizers in pearl millet (37). The current results corroborate the findings regarding the application of nano N in rice (40).

In addition to promoting growth and development, N also plays a crucial role in enhancing root length, surface area and biomass (41), which results in increased uptake of water and nutrients in plants. This may explain the higher K uptake in maize supplied with sufficient N through the combined application of nano and conventional N forms. The present findings of significant improvement in K uptake align closely with the results of studies on nano urea (40) and nano N application (39) in rice. It has also been reported that using 50% nano urea in combination with 50% conventional urea and biofertilizer recorded significantly higher K content in both grains and straw, along with total K uptake in black wheat (*Triticum aestivum* L.), as well as higher uptake of N, P and micronutrients, namely iron and zinc (38).

Influence of nano-fertilizers on nutrient use efficiency of maize

Influence of nano-fertilizers on agronomic efficiency (AE), physiological efficiency (PE) and apparent recovery efficiency (ARE) of maize

The higher results associated with agronomic efficiency of nitrogen (AE_N) and agronomic efficiency of phosphorus (AE_P) are primarily attributed to the lower levels of N and P applied to the soil. In contrast, equal levels of K were applied to all treatments except the control, resulting in significantly higher agronomic efficiency of potassium (AE_K) in T5, which is attributed to the higher yield correlated with it. The present findings are closely related to those of nano NPK application in baby corn (42), where the complete application of 125% of the recommended fertilizer dose (NPK) through nano NPK, with no application of conventional fertilizers to the soil, recorded higher AE. Similarly, lower N levels increase AE_N, in contrast to higher levels in maize, where the application of 60 kg ha^{-1} of N resulted in higher AE, while 180 kg ha^{-1} of N recorded lower AE (2). These findings also conform to the results observed in rice (43).

The higher physiological efficiency (PE) may be due to the plant's capacity to increase yield with each unit of nutrient uptake, leading to better accumulation and conversion of nutrients from source to sink (44). Furthermore, this increase in yield was primarily a result of the combined application of nano and conventional forms of N, an essential component of chlorophyll that enhances photosynthesis and subsequent growth and yield. It was observed that the increase in physiological efficiency in borage (*Borago officinalis* L.), a medicinal plant, can be attributed to the increase in chlorophyll and dry matter, which further contributes to higher yields (45). These results are in close agreement with findings from winter maize (12). In lettuce, administering 25% N in nano form and 25% N in conventional mineral form resulted in elevated physiological efficiency of nitrogen (PE_N) (46).

Reduced fertilizer application to the soil, which leads to increased nutrient uptake, may account for the elevated apparent recovery efficiency of nitrogen (ARE_N) and apparent recovery efficiency of phosphorus (ARE_P) values. In contrast, higher AE_K was mainly due to the higher yields obtained with increased uptake, as an equal dose of K was applied to all treatments except for the control. Nutrient recovery primarily depends on the soil's capacity to supply nutrients and on the inherent properties of the plant to take up and utilize these nutrients. Additionally, it also depends on the method of nutrient application (47). It has been stated that ARE decreases with an increase in fertilizer levels, as this reduces the efficiency of nutrient uptake (12). Plants cannot take up nutrients beyond a specific limit, which results in nutrient loss; thus, limited fertilizer levels reduce this loss by increasing the absorption efficiency of the plants. The application of 25% of the recommended dose of P with a full dose of N and K, along with root dipping and one foliar spray of nano DAP at 20-25 DAT in rice, recorded significantly higher AREP compared to other treatments, which was primarily due to the lower levels of soil application of P (43). This is also supported by findings in cabbage (44) and baby corn (42).

Influence of nano fertilizers on energy usage in maize

The higher energy of FYM and fertilizers accounted for 63.8% of the total energy input, while the absolute control recorded lower energy input. Supplementing conventional fertilizers with nano fertilizers reduces the overall energy requirements of the fertilizers. An investigation of the maize-fallow system in the Eastern Himalayas revealed that 59.3% of the input energy was contributed by manures and fertilizers (26). It was also noted that a significant share of energy input is attributed to the higher energy of fertilizers in conservation agriculture-based maize-wheat sequences (48). A study on Colocasia-based cropping systems further revealed that 83% of total energy consumption came from fertilizers, manures, non-renewable fuel (diesel) and seed inputs (24).

The higher energy output was observed because of higher crop yield as positive relation was observed between energy output and crop yield resulted in higher net energy (48). Similar results were also observed in maize crop (49). The variation in energy out put among treatments in the current experiments is mainly attributable to the differences in kernel and stover yield. These findings align closely with the energetic results observed in cabbage (44) and winter maize (12).

Production potential and yielding ability determine all the parameters discussed above and in the present study, the increase in yield was primarily due to the application of nano fertilizers alongside conventional fertilizers. Nitrogen is an important component of many amino acids, which are the building blocks of proteins. Its application promotes growth and development in plants, facilitating the effective translocation of accumulated nutrients from source to sink, ultimately resulting in higher yields. The higher yields obtained in the 75% RDN + nano-N treatment are the main factors contributing to improved energy use efficiency, productivity, and profitability. It has been stated that energy use efficiency and productivity are directly correlated to the production capacity of the crop (26). In maize, the higher energy use efficiency and productivity stem from a greater ratio of output energy to input energy, as well as a higher yield-to-input energy ratio, both of which depend on elevated yields (12). Many other researchers (44, 48, 50) have observed similar findings.

Soil available nutrients after harvest of maize crop

The higher availability of nutrients in the soil was observed in T1 (RDF + FYM) due to the unavailability of applied nutrients to the crop for various reasons, such as fixation and being in an unavailable form. It was noted that 100% of the RDN and 25% of the foliar application of nano N left more N available in the soil after the lettuce harvest (46). Similar results were also observed in maize at harvest, as reported by the researcher (1).

Conclusion

The application of 75% RDN + nano N (T5) resulted in significantly higher maize grain and stover yields of 9,654 kg ha^{-1} and 9,515 kg ha^{-1}, respectively, which represent increases of 10.20% and 9.29% in grain and stover yield compared to the conventional practice of RDF + FYM (T1). This treatment also recorded higher nutrient uptake, with values of 299.22 kg ha^{-1} of N, 55.56 kg ha^{-1} of P and 208.26 kg ha^{-1} of K, indicating the efficient utilization of non-renewable resources. Nano fertilizers improved nutrient use efficiency while minimizing energy consumption compared to conventional fertilizer application practices.

Acknowledgements

The authors thank the Department of Agronomy and Zonal Agricultural Research Station, UAS, Bangalore.

Authors' contributions

AKK participated in data recording, conducted statistical analysis, and wrote the original draft. JHM conceptualized the study, provided guidance, and finalized the data. VMGG contributed to manuscript writing, reviewing, and editing. PN was involved in manuscript writing and reviewing. KDJ and DAR participated in reviewing and editing.

Compliance with ethical standards

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

Ethical issues: None

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