Maize Journal (April 2026) 15(1): 21-27

RESEARCH PAPER

Nano phosphorus feasibility in sandy loam soils for maize-wheat system of western IGP

A. K. Singh[1] • Ritesh[1] • S. D. Bamboriya[1] • S. L. Jat[2] • D. M. Mahala[1]

Abstract: The phosphorus is the most expensive nutrient in crop production exhibiting the lowest use efficiency amongst the major nutrients. In response to the growing concern about potential negative impact of large-scale chemical fertilizer applications on soil health, ecosystem, food chain, and crop production economics, nano-fertilization have gained importance in the recent past. Nano-DAP (diammonium phosphate) was evaluated in maize-wheat cropping system for two at Ludhiana, Punjab, India. The results showed that seed dressing with nano-DAP @ 5 ml/kg seed + 75% recommended dose of N and P through conventional DAP + nano-DAP foliar spray @ 4 ml/l water resulted in at par grain yield with 100% N&P application in both maize and wheat. However, replacing 25% of the recommended dose of fertilizer with nano-DAP resulted in slightly higher cost of cultivation (Rs. 550/ha with unsubsidized DAP and Rs. 2250/ha with subsidized DAP) but it gave on par net profit, and soil N and P availability. These findings suggest that nano-DAP could be a feasible option to partially substitute the nitrogen and phosphorus based conventional fertilizers in maize-wheat system.

Keywords: Crop productivity • Di ammonium phosphate • Fertilizer source • Economic profitability • Nano-fertilizer

✉ S. D. Bamboriya: sbamboriya93@gmail.com

[1]ICAR-Indian Institute of Maize Research, Ludhiana-141004, Punjab, India

[2]ICAR-Indian Institute of Maize Research, Delhi Unit, New Delhi-110012, India

Received: 28 August 2025/ Accepted: 26 November 2025

Introduction

Cereals play a crucial role in food and nutritional security by providing a significant portion of the dietary energy intake and essential nutrients for a humankind, especially in lower-income countries (Ramadas *et al.,* 2019). The maize-wheat rotation stands out as one of the widely adopted cereal-based cropping systems in India, encompassing an extensive area of over 1.8 million hectares (Radheshyam *et al.,* 2024). Both maize and wheat are considered heavy nutrient feeders, requiring substantial amounts of fertilizers, particularly nitrogen (N) and phosphorus (P), to support their growth, development, and yield potential. Meeting the nutrient demands of these crops is crucial for maximizing productivity and ensuring agricultural sustainability.

Diammonium phosphate (DAP) is the most widely used phosphatic fertilizer (17.2 million tonnes) (Maqsood *et al.,* 2022). India, the leading global consumer of DAP, heavily relies on imports to meet approximately 50–55 per cent of its total demand (Anonymous, 2018). Presently, Indian farmers are grappling with a scarcity of DAP fertilizer and an unprecedented surge in its prices. The shortage of DAP has posed significant challenges to agricultural productivity and sustainability in the region. Additionally, the central government is burdened with a substantial subsidy on DAP, amounting to Rs. 2501 per 50 kg bag (Department of Fertilizers, 2022). The production and transportation of chemical fertilizers involve significant energy expenditure, and their field application exerts considerable environmental and ecological consequences (Solanki *et al.,* 2015). Moreover, the high solubility of applied DAP fertilizer results in substantial losses through leaching or runoff, leading to financial penalties and lowered nutrient use efficiencies, often remaining below 30-35% for N and 18-20% for P (Kumar *et al.,* 2023). Improving nutrient use efficiency is crucial through the adoption of more efficient, environmentally friendly and cutting-edge agronomic technologies.

In recent years, nanotechnology has gained attention and significance in the fields of plant science and agriculture. Nanotechnology-based fertilizers are regarded as next-generation fertilizers due to their ability to produce comparable yields with smaller quantities, simultaneously enhancing soil health and reducing air and water pollution (Gade *et al.,* 2023). In contrast to conventional DAP, nano-DAP is an indigenous, cheaper and non-subsidized liquid fertilizer with >90% nutrient-use efficiency under field conditions, and its production is both energy-efficient and resource friendly (Singh *et al.,* 2017). Nano-fertilizers exhibit a surface area over 10,000 times more than conventional fertilizers, showcasing distinctive magnetic properties, electronic states, catalytic reactions and higher reactivity (Raliya *et al.,* 2018; Grillo *et al.,* 2021; Kumar *et al.,* 2021).

Therefore, conducting field-level tests on the newly developed nano-DAP was imperative to assess its impact on crop productivity, profitability, and soil health within the maize-wheat cropping system.

Materials and methods

The experiment was conducted for two consecutive years (2021-22 and 2022-23) at fixed site at the research farm of ICAR-Indian Indian Institute of Maize Research, Ladhowal, Ludhiana, India. The study site is located at 30°58' N latitude, 75°44' E longitude and at 241 m above mean sea level. The soil of the experimental site was sandy loam in texture with a low level of soil organic carbon (0.4%) and available N (83.9 kg/ha) and medium levels of available P (16.4 kg/ha) and available K (218 kg/ha). Ten different treatments were tested using a randomized complete block design with three replications (Table 1). Altogether four doses of N and P (0, 50%, 75% and 100% of recommended) were evaluated with varying levels of nano-DAP. The 100% recommended dose of nutrients (RDF) for both maize and crops were 120 kg N, 60 kg P_2O_5 and 30 kg K_2O per hectare. Urea, DAP and muriate of potash (MOP) were used to supply N, P and K, respectively. In both the crops, 1/3rd dose of N and full doses of P and K were applied at sowing. The remaining 2/3rd dose of N was applied in two equal splits at knee-height and tasseling stages in maize and at maximum tillering and ear head emergence stages in wheat crop. The nano-DAP formulation used in the study

Table 1. Details of treatments executed to maize and wheat crops

Treatment notation	Treatment description	Nutrient applied (kg/ha)			
		Nano DAP		Total	
		N	P_2O_5	N	P_2O_5
T_1	Control (no N & P application)	0.0	0.0	0.0	0.0
T_2	100% recommended dose of N & P	0.0	0.0	120.0	60.0
T_3	75% recommended dose of N & P	0.0	0.0	90.0	45.0
T_4	50% recommended dose of N & P	0.0	0.0	60.0	30.0
T_5	75% recommended dose of N & P + Seed treatment with nano-DAP @ 5 ml/kg seed + One foliar spray with nano-DAP @ 2 ml/litre of water at 30-35 DAS	0.10	0.21	90.1	45.2
T_6	75% recommended dose of N & P + Seed treatment with nano-DAP @ 5 ml/kg seed + Foliar spray with nano-DAP @ 4 ml/litre of water at 30-35 DAS	0.20	0.40	90.2	45.4
T_7	50% recommended dose of N & P + Seed treatment with nano-DAP @ 5 ml/kg seed + Foliar spray with nano-DAP @ 2 ml/litre of water at 30-35 DAS	0.10	0.21	60.1	30.2
T_8	50% recommended dose of N & P + Seed treatment with nano-DAP @ 5 ml/kg seed + Foliar spray with nano-DAP @ 4 ml/litre of water at 30-35 DAS	0.10	0.21	60.1	30.2
T_9	50% recommended dose of N & P + Seed treatment with nano-DAP @ 5 ml/kg seed + Foliar spray with nano-DAP @ 2 ml/litre of water at 30-35 DAS & 45 DAS	0.20	0.40	60.2	30.4
T_{10}	50% of recommended dose of N & P + Seed treatment with nano-DAP @ 5 ml/kg seed + Foliar spray with nano-DAP @ 4 ml/litre of water at 30-35 and 45 DAS	0.20	0.40	60.2	30.4

had 8.0% N (w/v) and 16.0% P_2O_5 (w/v). The seeds were treated with nano-DAP @ 5 ml/kg seed before sowing as per the treatment requirement. Foliar spray of nano-DAP (2 ml or 4 ml/litre) was made at 30 days after sowing (DAS) and/or 45 DAS as per the treatment using 600 litre water/ha. Battery-operated knapsack sprayer fitted with hollow cone nozzle was used for foliar application of nano-DAP during evening hours.

The maize crop was sown on 15th July, 2021 and 3rd July 2022, while wheat sowing was done on 5th November, 2021 and 23th October 2022. The maize variety 'CP-858' was sown at spacing of 60 cm × 20 cm using multi crop planter. The 'PBW-869' variety of wheat was sown at row to row spacing 25 cm with 100 kg seed/ha. Pre- (atrazine 50% WP @ 1.2 kg/ha) and post-emergence (Tembotrione 34.4% @ 120 g/ha) herbicides were applied to manage the weed problem in maize. Chlorantraniliprole 18.5% SC was sprayed at two times to safeguard the crops against fall army worm. Irrigations were applied at crucial crop growth stages in maize (knee- height, tasseling, silking) and wheat (crown root initiation, maximum tillering, flowering, milk). Maize received a total of 4 irrigations, while wheat received 6 irrigations per season. In wheat crop, Pendimethalin @ 1.5 kg/ha was applied just after sowing and 2,4-D @ 1.2 kg/ha was sprayed at 30 DAS for weed control. Maize was harvested on 1st November, 2021 and 17th October 2022. While harvesting of wheat was carried out on 9th April, 2021 and 6th April 2022. The crops were harvested from the inner rows of plots, leaving border rows on both sides to minimize any potential border effects. The harvested products were sun-dried before the threshing operation, and subsequently, both grain and stover/straw yields were weighed separately. The cultivation costs, net returns, and the benefit-cost ratio (B:C) with and without DAP subsidy across various treatments were calculated based on the prevailing market prices. The production costs include expenses related to a spectrum of farm resources, inputs, and farm operations, including seeds, fertilizers, pesticides, labor, machinery, tillage/ sowing operations, irrigation, plant protection, harvesting and threshing. Net returns were computed by subtracting production costs from gross returns of the respective treatment. The benefit to cost ratio was worked out by dividing the net returns by the cost of cultivation.

Soil samples were collected from two depths, 0-15 cm and 15-30 cm, using a core sampler to assess the effects of conventional fertilizer and nano fertilizer on the soil fertility after completion of 2-years experiment. The collected soil samples were shade-dried, grounded, and sieved through a 2-mm mesh before analysis to determine the available N and P as well as organic carbon content. Analysis of variance was performed using SAS software (version 9.4) to assess the significance of the results (Gomez and Gomez, 1984). For comparing treatments means, LSD (Least Significant Difference) test at a 95% confidence interval was conducted.

Results and discussion

Yield and harvest index

The highest maize grain yield was achieved in T_6 during 2021 and T_2 during 2022 (Table 2). Both treatments consistently produced statistically similar grain yields over the years. This suggests that substituting 25% of RDF with nano-DAP, applied through seed dressing at 5 ml/ kg seed and foliar spray at 4 ml/l, resulted in a yield comparable to that of 100% RDF. The sustained crop yields resulting from the application of nano fertilizers may be attributed to enhanced uptake, transport and absorption of nutrient by the plants (Rose *et al.,* 2015; Abdel-Aziz *et al.,* 2016; Singh *et al.,* 2017). Moreover, the application of nano fertilizers through seed dressing improves seed germination and enhances the vigor of seedlings, thereby contributing to overall plant growth, development and yield (Najafi *et al.,* 2016). In contrast, the plot where N & P application was omitted (T_1), recorded the lowest grain yield which was 89.0 and 92.6% lesser than 100% RDF (Figure 1). Poor vegetative growth and compromised physiological characteristics contributed to the low yield at low nutrient level (Bamboriya *et al.,* 2023). Application of 50% RDF (T_4) faced 27.2 and 29.8% yield reduction over T_2; although the yield gaps were slightly compensated with inclusion of nano-DAP in the fertilizer plan. Furthermore, a yield reduction of 7.3-16.7% was observed when N and P doses were cut down by 25% (T_3) than 100% RDF. But conjunct application of 75% RDF with nano DAP (T_5 and T_6) resulted in a yield reduction of only up to 3.0% over 100% RDF, respectively. Similar trends were also observed for stover yield across the years. The harvest index was higher with T_{10}, while control registered the least harvest index (Table 2).

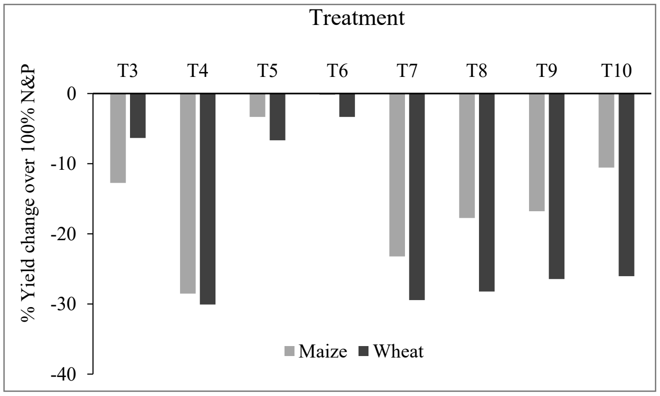

Figure 1. Per cent yield changes in maize and wheat in various nano-DAP applied treatments over 100% N&P (mean of two years)

In wheat, T_5 and T_6 recorded comparable yields with T_2 (Table 2). Nanomaterials, owing to their potential for a slow and consistent release of essential nutrients, could have enhanced nutrient use efficiency and overall yield (Jyothi and Hebsur, 2017; Preetha and Balakrishnan, 2017; Kalia and Sharma, 2019). Moreover, the sustained yield with nano-DAP can be attributed to an improvement in seed germination, seedling growth, nitrogen metabolism, photosynthetic activity, and protein synthesis (Iqbal *et al.,* 2019). Whereas, application of 50% of the recommended dose of N and P, exhibited significantly lower yields (29.9 and 30.2%) compared with T_2 (Figure 1). The combination of seed dressing and foliar application of nano-DAP in addition of 50% RDF, improved the grain yield by 5.7% over only 50% RDF application. The application of 100% RDF resulted in significantly higher straw yields (6.9 and 5.4 t/ha) surpassing all other treatments except for T_3, T_5 and T_6. The harvest index was non significantly differed among the various treatments.

Economics

Result showed that control plot incurred the lowest cost owing to nil charge of N&P fertilizers. The 100% RDF was also found to be slightly more cost-effective due to lesser expenditures on conventional fertilizers application. Treatments with inclusion of nano DAP recorded higher cost of cultivation over T_2 in both crops (Table 3&4). Production costs were significantly higher when using non-subsidized DAP, primarily due to its high price of Rs. 80 per kg nearly three times the cost of subsidized DAP, which is priced at just Rs. 27 per kg. An additional cost of 2250 Rs./ha was incurred due to the application of nano-DAP with 75% RDF (T_6) over 100% RDF across the crops when considering subsidized DAP. On the other hand, when unsubsidized DAP was taken into account, the additional cost for T_6 over T_2 was only Rs. 550/ha.

Control plot, which excluded N&P application, resulted in the poorest yield and therefore, generated the lowest economic returns. Conversely, optimal nutrient supply in both 100% and 75% recommended N&P+ nano-DAP provided yield advantage and improved economic returns as well. For subsidized DAP, plots receiving nano-

Table 2. Grain yield, stover/straw yield and harvest index of maize and wheat as affected by different combinations of nano-DAP application

Treatment*	Maize						Wheat					
	Grain yield (t/ha)		Stover yield (t/ha)		Harvest index (%)		Grain yield (t/ha)		Straw yield (t/ha)		Harvest index (%)	
	2021	2022	2021	2022	2021	2022	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T_1	0.6^{d}	0.4^{c}	1.2^{d}	1.2^{c}	30.5^{ab}	21.8^{c}	0.7^{c}	0.9^{c}	1.5^{c}	1.3^{c}	31.2^{a}	40.8^{a}
T_2	5.5^{ab}	5.4^{a}	10.5^{ab}	8.3^{a}	31.4^{ab}	37.1^{a}	4.5^{a}	4.7^{a}	6.9^{a}	5.4^{a}	39.7^{a}	46.6^{a}
T_3	5.1^{ab}	4.5^{bc}	9.3^{b}	7.7^{ab}	31.1^{ab}	31.6^{b}	4.2^{a}	4.3^{b}	6.1^{a}	4.7^{ab}	40.9^{a}	48.4^{a}
T_4	4.0^{c}	3.8^{c}	7.7^{c}	6.0^{b}	30.7^{ab}	35.0^{ab}	3.2^{b}	3.3^{b}	5.2^{b}	4.5^{b}	38.5^{a}	42.2^{a}
T_5	5.7^{a}	4.9^{b}	10.5^{ab}	7.4^{ab}	30.8^{ab}	35.4^{ab}	4.2^{a}	4.4^{a}	6.3^{a}	4.9^{ab}	40.0^{a}	47.9^{a}
T_6	5.8^{a}	5.1^{ab}	10.8^{a}	7.0^{ab}	30.3^{ab}	37.8^{a}	4.3^{a}	4.6^{a}	6.7^{a}	4.8^{ab}	39.7^{a}	48.8^{a}
T_7	4.4^{bc}	4.0^{c}	8.0^{bc}	7.2^{ab}	30.1^{ab}	32.8^{ab}	3.2^{b}	3.3^{b}	5.3^{b}	4.5^{b}	38.2^{a}	42.4^{a}
T_8	4.9^{b}	4.2^{c}	8.9^{bc}	6.5^{b}	31.7^{ab}	35.9^{ab}	3.2^{b}	3.4^{b}	5.1^{b}	4.6^{b}	38.8^{a}	41.9^{a}
T_9	4.7^{bc}	4.5^{bc}	8.5^{bc}	7.6^{ab}	31.7^{ab}	34.1^{ab}	3.3^{b}	3.5^{b}	4.9^{b}	4.6^{b}	39.9^{a}	43.3a
T_{10}	5.2^{ab}	4.6^{bc}	9.3^{b}	6.5^{b}	32.1^{a}	37.7^{a}	3.3^{b}	3.5^{b}	5.3^{b}	4.4^{b}	38.2^{a}	43.1^{a}

*For treatments details please refer Table 1. The values with at least one similar letter in a column are non-significant to each other.

Table 3. Production economics of maize as affected by different combinations of nano-DAP application

Treatment*	Cost of cultivation (× 000 Rs./ha)				Net returns (× 000 Rs./ha)				B: C ratio			
	Subsidized DAP		Non-subsidized DAP		Subsidized DAP		Non-subsidized DAP		Subsidized DAP		Non-subsidized DAP	
	2021	2022	2021	2022	2021	2022	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T_1	39.9	42.6	39.9	42.6	-25.8^{d}	-32.3^{e}	-25.8^{d}	-32.3^{d}	-0.65^{c}	-0.76^{d}	-0.65^{c}	-0.76^{d}
T_2	45.1	48.2	52.1	55.1	83.7^{ab}	77.5^{a}	76.7^{ab}	70.5^{a}	1.86^{a}	1.61^{a}	1.47^{ab}	1.28^{a}
T_3	44.0	47.0	49.3	52.2	73.2^{b}	62.4^{bc}	67.9^{b}	57.1^{b}	1.66^{ab}	1.33^{b}	1.38^{ab}	1.09^{b}
T_4	42.9	45.8	46.4	49.3	51.0^{c}	44.1^{d}	47.5^{c}	40.5^{c}	1.19^{b}	0.96^{c}	1.02^{b}	0.82^{c}
T_5	46.0	48.9	51.2	54.2	87.9^{ab}	65.2^{bc}	82.6^{ab}	59.9^{ab}	1.91^{a}	1.33^{b}	1.61^{a}	1.10^{ab}
T_6	47.4	50.4	52.7	55.6	93.6^{a}	67.5^{b}	88.3^{a}	62.1^{ab}	1.97^{a}	1.34^{b}	1.68^{a}	1.12^{ab}
T_7	44.9	47.7	48.4	51.2	56.1^{c}	49.9^{cd}	52.5^{bc}	46.4^{c}	1.25^{b}	1.05^{c}	1.09^{b}	0.91^{c}
T_8	46.3	49.2	49.8	52.7	66.0^{bc}	48.7^{cd}	62.5^{bc}	45.1^{c}	1.42^{b}	0.99^{c}	1.25^{b}	0.86^{c}
T_9	46.7	49.6	50.2	53.1	60.8^{bc}	57.0^{c}	57.4^{bc}	53.4^{bc}	1.30^{b}	1.15^{bc}	1.14^{b}	1.01^{bc}
T_{10}	49.6	52.5	53.1	56.0	70.5^{bc}	54.2^{c}	67.0^{ab}	50.5^{bc}	1.42^{b}	1.03^{c}	1.26^{b}	0.90^{c}

*For treatments details please refer Table 1. The values with at least one similar letter in a column are non-significant to each other.

Table 4 Production economics of wheat as affected by different combinations of nano-DAP application

Treatment*	Cost of cultivation (× 000 Rs./ha)				Net returns (× 000 Rs./ha)				B: C ratio			
	Subsidized DAP		Non-subsidized DAP		Subsidized DAP		Non-subsidized DAP		Subsidized DAP		Non-subsidized DAP	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T_1	31.7	35.3	31.7	35.3	-8.9^{e}	-11.2^{c}	-8.9^{d}	-11.2^{c}	-0.28^{e}	-0.32^{c}	-0.28^{d}	-0.32^{c}
T_2	36.9	41.0	43.8	47.9	78.6^{a}	77.3^{a}	71.7^{a}	70.4^{a}	2.13^{a}	1.89^{a}	1.64^{a}	1.47^{a}
T_3	35.8	39.7	41.0	44.9	70.5^{b}	70.4^{a}	65.3^{ab}	65.2^{a}	1.97^{ab}	1.77^{a}	1.59^{a}	1.45^{a}
T_4	34.7	38.5	38.1	42.0	47.3^{c}	46.5^{b}	43.9^{c}	43.0^{b}	1.36^{c}	1.21^{b}	1.15^{b}	1.02^{b}
T_5	37.8	41.7	42.9	46.9	68.4^{b}	69.2^{a}	63.3^{b}	64.0^{a}	1.81^{b}	1.66^{a}	1.48^{a}	1.36^{a}
T_6	39.2	43.1	44.4	48.3	71.6^{ab}	70.4^{a}	66.4^{ab}	65.2^{a}	1.83^{b}	1.63^{a}	1.50^{a}	1.35^{a}
T_7	36.6	40.5	40.1	44.0	46.2^{c}	45.3^{b}	42.7^{c}	41.8^{b}	1.26^{cd}	1.12^{b}	1.06^{b}	0.95^{b}
T_8	38.1	41.9	41.5	45.4	45.3^{c}	45.8^{b}	41.9^{c}	42.3^{b}	1.19^{cd}	1.09^{b}	1.01^{bc}	0.93^{b}
T_9	38.5	42.3	41.9	45.8	44.6^{c}	48.3^{b}	41.2^{c}	44.8^{b}	1.16^{d}	1.14^{b}	0.98^{bc}	0.98^{b}
T_{10}	41.4	45.2	44.8	48.7	42.9^{c}	46.7^{b}	39.5^{c}	43.2^{b}	1.04^{d}	1.03^{b}	0.88^{c}	0.89^{b}

*For treatments details please refer Table 1. The values with at least one similar letter in a column are non-significant to each other.

DAP application, irrespective of N & P doses, exhibited a higher cost of cultivation over 100% RDF, except for T_7 in both crops. In the 2021 maize crop, the highest net returns (93.6×000 Rs./ha) and B:C (1.97) were achieved with T_6, comparable to T_5 and T_2. However, in 2022, the highest net returns (77.5 × 000 Rs./ha) as well as B:C (1.61) were obtained in T_2, which was statistically superior over other treatments. In wheat, T_2 recorded significantly higher net returns (78.6 and 77.3 × 000 Rs./ha) and B:C (2.13 and 1.89) during both the years. However, T_3, T_5 and T_6 recorded similar economic returns with T_2 for wheat during both the years. The comparable trend was also observed for unsubsidized DAP.

Soil Available N and P

Soil fertility was significantly influenced by different fertilizer treatments in the maize-wheat system (Table 5). The recommended N & P application (T_2) registered the highest values for soil available N and P content at 0-15 cm and 15-30 cm depths. Soil available N and P content under 75% RDF + nano-DAP (T_6) were comparable to

Table 5. Effect of different combinations of nano-DAP application on soil N, P and organic carbon after completion of two years crop cycle

Treatment*	Available N (kg/ha)		Available P (kg/ha)		Soil organic carbon (%)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
T_1	67.8^d	28.1^d	14.1^c	6.57^d	0.42^a	0.30^a
T_2	85.0^a	47.9^a	16.9^a	9.15^a	0.44^a	0.31^a
T_3	80.6^b	43.0^b	15.8^b	8.79^{ab}	0.43^a	0.32^a
T_4	78.2^b	38.1^c	15.3^b	8.44^b	0.42^a	0.34^a
T_5	80.4^b	42.7^b	16.0^{ab}	8.22^{bc}	0.43^a	0.34^a
T_6	81.4^{ab}	44.7^a	16.3^{ab}	8.55^{ab}	0.42^a	0.34^a
T_7	76.1^c	38.1^c	15.5^b	7.82^{bc}	0.44^a	0.30^a
T_8	76.0^c	37.9^c	15.2^b	7.83^{bc}	0.43^a	0.32^a
T_9	75.2^c	38.7^c	15.3^b	7.68^c	0.42^a	0.33^a
T_{10}	75.5^c	39.9^c	15.5^b	7.49^c	0.44^a	0.32^a
Initial fertility	83.9	45.6	16.4	8.82	0.43	0.32

*For treatments details please refer Table 1. The values with at least one similar letter in a column are non-significant to each other.

that under 100% RDF, indicating the absence of nutrient mining when 25% RDF was substituted with nano-DAP. The seed dressing with nano-DAP likely improved root growth and morphology, leading to increased efficiency in utilizing the applied nutrients (Tarafdar *et al.,* 2014), contributed to the prevention of nutrient mining at 75% recommended dose of fertilizer (RDF) combined with nano-DAP. In comparison to the initial soil fertility, a slight improvement in soil available N & P contents were observed when 100% RDF was applied. The application of 0% (control) and 50% RDF, with or without nano-DAP, resulted in depleted soil fertility compared to the initial soil fertility attributed to a negative balance between nutrient uptake and nutrient supply. Therefore, it is recommended to apply at least 75% of the recommended N & P to avoid nutrient mining. The soil organic carbon content was non-significantly affected by the various treatments.

Conclusions

The findings unequivocally indicate the effectiveness of 75% RDF + nano-DAP, which produced comparable yield and profit to 100% RDF with a 25% reduction in fertilizer use. Importantly, 75% RDF + nano-DAP did not deplete soil fertility compared to 100% RDF, signifying no adverse long-term effects on soil health. Therefore, it can be inferred that application of nano-DAP (applied as seed dressing @ 5 ml/kg seed and foliar spray @ 4 ml/litre water) could effectively replace 25% of conventional DAP without compromising yield and economic profitability in both the crops under maize-wheat system.

Acknowledgements

Research was supported by Indian Council of Agricultural Research, Department of Agricultural Research and Education, Government of India. We are thankful to IFFCO for providing necessary assistance during the conduct of the study.

References

Abdel-Aziz H. M. M., Hasaneen, M. N. A. & Ome A. M. (2016). Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Spanish Journal of Agricultural Research,* **14**(1): e0902.

Anonymous. (2018). Indian Fertilizers Scenario. Department of Fertilizers, Ministry of Chemical and Fertilizers. Retrieved from: https://www.fert.nic.in/sites/default/files/2019-09/Fertilizers-Scenario-2018.pdf

Bamboriya, S. D., Dhar, S., Upadhyay, P. K., Dass, A., Meena, R. P. & Garg, K. (2023). Evaluation of maize (*Zea mays*) genotypes under different nitrogen levels in a Trans-Gangetic Plains region. *Indian Journal of Agronomy,* **68** (4): 368-372.

Department of Fertilizers (2022). Retrieved from https://fert.gov.in/documents/act-policies/phosphatic-and-potassic-pk-policy.

Gade, A., Ingle, P., Nimbalkar, U., Rai, M., Raut, R., Vedpathak, M., Jagtap, P. & Abd-Elsalam, K. A. (2023). Nano fertilizers: The next generation of agrochemicals for long-term impact on sustainability in farming systems. *Agrochemicals,* **2**(2): 257-278. https://doi.org/10.3390/agrochemicals2020017

Gomez, K. A. & Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research*. An International Rice Research Institute Book 2nd edn. Wiley, New York.

Grillo, R., Mattos, B. D., Antunes, D. R., Forini, M. M. L., Monikh, F. A. & Rojas, O. J. (2021). Foliage adhesion and interactions with particulate delivery systems for plant nanobionics and intelligent agriculture. *Nano Today,* **37**: https://doi.org/10.1016/j.nantod.2021.101078.

Iqbal, M., Umar, S., & Mahmooduzzafar. (2019). Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants. *Plant Potential,* 473–505. doi:10.1007/978-3-030-05569-1_19

Jyothi, T. V. & Hebsur, N. S. (2017). Effect of nanofertilizers on growth and yield of selected cereals - a review. *Agriculture,* **38**. doi:10.18805/ag.v38i02.7942

Kalia, A., Sharma, S. P. & Kaur, H. (2019). Nanoscale fertilizers: harnessing boons for enhanced nutrient use efficiency and crop productivity. In: Abd-Elsalam KA, and Prasad R (eds) Nanobiotechnology applications in plant protection: volume 2. *Nanotechnology in the Life sciences*. Cham, Switzerland: Springer International Publishing, pp. 191–208. doi:10.1007/978-3-030-13296-5_10

Kumar, N., Samota, S. R., Venkatesh, K. & Tripathi, S. C. (2023). Global trends in use of nano-fertilizers for crop production: Advantages and constraints – A review. *Soil and Tillage Research,* **228**: 105645.

Kumar, Y., Singh, T., Raliya, R. & Tiwari, K. N. (2021). Nano fertilizers for sustainable crop production, higher nutrient use efficiency and enhanced profitability. *Indian Journal of Fertilizers,* **17**: 1206–1214.

Maqsood, M. A., Naqsh-e-Zuhra, Ashraf, I., Rasheed, N. & Shah, Z. U. H. (2022). Sources of nitrogen for crop growth: Pakistan's case. In: Aziz T, Wakeel A, Watto MA, Sanaullah M, Maqsood MA and Kiran A (eds) *Nitrogen Assessment*. Academic Press, pp. 13-28.

Najafi, D. M., Mikhak, A., Kassaee, M. Z. & Maghari, A. (2016). Effects of nano Fe/SiO_2 fertilizers on germination and growth of barley and maize. *Archives of Agronomy and Soil Science,* **63**(6): 817-826.

Preetha, P. S. & Balakrishnan, N. (2017). A review of nano fertilizers and their use and functions in soil. *International Journal of Current Microbiological and Applied Science,* **6**(12): 3117–3133. doi:10.20546/ijcmas.2017.612.364

Radheshyam, Jat, S. L., Jat, M. L., Parihar, C. M., Jat, H. S., Singh, A. K., Bijarniya, D., Padhan, S. R., Kadam, P. V. & Kumar, M. (2024) On-farm evidence on breaking yield barriers through optimizing wheat cropping system in Indo Gangetic Plain. *European Journal of Agronomy*, **159**: e127256.

Raliya, R., Saharan, V., Dimpka, C. & Biswas, P. (2018). Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. *Journal of Agricultural and Food Chemistry,* **66**(26): 6487–6503.

Ramadas, S., Kumar, T. K. & Singh, G. P. (2019). Wheat production in India: Trends and prospects. In: Shah F, Khan Z, Iqbal A, Turan M, and Olgun M (eds) *Recent Advances in Grain Crops Research*. IntechOpen. doi: 10.5772/intechopen.86341

Rose, H. B. L., Rubenecia, M. R., Rubenecia, U., Ultra, V. & Lee, S. C. (2015). Nano-fertilizer affects the growth, development, and chemical properties of rice. *International Journal of Agronomy and Agricultural Research,* **7**(1): 105-117.

Singh, U., Praharaj, C. S., Kumar, N., Deo, M. M. & Kumar, L. (2017). Enhancing nutrient use efficiency through next generation fertilizers in field crops. Training Manual, ICAR-Indian Institute of Pulses Research, Kanpur, Uttar Pradesh-208 024, India. pp. 229.

Solanki, P., Bhargava, A., Chhipa, H., Jain, N. & Panwar, J. (2015). Nano-fertilizers and their smart delivery system. In: Rai M, Ribeiro C, Mattoso L and Duran N. (eds). *Nanotechnologies in Food and Agriculture*. Springer, Cham. https://doi.org/10.1007/978-3-319-14024-7_4

Tarafdar, J. C., Raliya, R., Mahawar, H. & Rathore, I. (2014). Development of zinc nanofertilizer to enhance crop production in pearl millet (*Pennisetum americanum*). *Agricultural Research,* **3**: 257–262.