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Nano DAP augments productivity, phosphorus use efficiency, and profitability of spring wheat

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Agriculture is undergoing a transformation through innovations like nano fertilizers, which offer the potential to enhance productivity and sustainability. This study aimed to evaluate the effectiveness of nano DAP to improve growth, yield attributes, nutrient uptake, and economic viability in wheat (*Triticum aestivum* L.) cultivation. A two-year field experiment during the *rabi* seasons of (2022–23, 2023-2024) was conducted at the ICAR-Indian Agricultural Research Institute, New Delhi, India, using a randomized complete block design with ten treatments. These included a control (zero P), 50%, 75%, and 100% of the recommended dose of phosphorus (RDP), with or without nano DAP sprays (2.5 ml and 5 ml L^{-1}), replicated three times. Results demonstrated that the application of 100% RDP combined with two foliar sprays of nano DAP significantly increased grain yield by 34.8% and 14.7% in the 2022–2023 and 2023–2024 seasons, respectively, compared to the control. However, in 2022-23, P_{50} + $nano_{2.5}$ ml L^{-1} resulted in a 13.7% reduction in yields, while P_{50} + $nano_5$ ml L^{-1} showed a 7.8% decrease compared to P_{100}. In 2023-24, both treatments achieved yields comparable to P_{100}. Similarly, P_{75} + nano recorded yields on par with P_{100}. Additionally, grain phosphorus (P) and nitrogen (N) uptake, showed substantial increases of 69.9% and 42.2% for P, and 54.2% and 26.7% for N in P_{100} across the two seasons, compared to control. Economic analysis revealed higher net returns of US $ 1,022.30 and US $ 1,248.90 ha^{-1} $year^{-1}$ in 2022–2023 and 2023–2024, respectively. Reducing the P application to 75% RDP with two foliar sprays of nano DAP (5 ml L^{-1}) resulted in wheat yields of 4.25 t ha^{-1} and 6.04 t ha^{-1} in 2022–2023 and 2023–2024, respectively, which were statistically comparable to the yields achieved with 100% RDP. This treatment also improved N uptake (84.2, 125.0 kg ha^{-1}), P uptake (20.4, 24.2 kg ha^{-1}), and net returns (US $ 958.60, US $ 1,197.10 ha^{-1} $year^{-1}$) during 2022–23 and 2023–24, respectively. Thus, demonstrating its potential as an economically viable and environmentally sustainable alternative to conventional P_{100} application.

Keywords Foliar spray, Nano DAP, Nutrient uptake, Phosphorus, Yield

Global population, currently estimated at 7.7 billion is projected to grow exponentially, reaching 9.7 billion by 2050. This population surge will necessitate a 70% increase in food production compared to current production[1]. Wheat, which provides 20% of the protein consumed globally, is a staple food crop for nearly one-third of the world's population[2]. Consequently, wheat production must increase to 60% by 2050 to meet the nutritional demands of the growing population[3]. Currently, wheat is cultivated on 222.8 million hectares (Mha), with a global production of 790.5 million tonnes (Mt)[4]. In India, wheat accounts for approximately 31.40 Mha, with an annual production of 110.55 Mt and an average productivity of 3,248 kg ha^{-1} in 2022–23[5]. A critical factor in achieving this goal is phosphorus (P), a nutrient essential for promoting early plant growth, root development, and crop maturity. Despite its significance, phosphorus is the second most limiting nutrient in global agriculture after nitrogen[6], with approximately 5.7 billion hectares of farmland affected by phosphorus deficiency[7], a significant challenge that restricts agricultural productivity. As a result, substantial amounts of phosphorus fertilizers are required to achieve optimal crop yields[8]. Currently, phosphorus availability in cultivated soils primarily depends on the use of chemical fertilizers. This dependence poses significant challenges to achieving sustainable crop

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productivity and meeting global food demands. To overcome this, selecting the appropriate fertilizer types, application rates, and methods is crucial[9].

In India, phosphorus is of particular importance due to the country's lack of high-quality indigenous phosphate rock deposits, resulting in a heavy reliance on imports[10]. Mineral phosphate fertilizers, such as diammonium phosphate (DAP), single super phosphate (SSP), and triple super phosphate (TSP), are extensively used to meet crop P demand and mitigate yield losses[11]. Despite their widespread application, only 5–25% of the applied mineral phosphorus is absorbed by plants during the growing season, as much of it precipitates or adsorbs onto soil particles, becoming unavailable to plants[12]. This low phosphorus use efficiency (PUE), often limited to 10–20%[13,14], is a critical barrier to improving wheat production worldwide. The inefficiency of conventional phosphorus fertilizers has significant implications. Global demand for P-based fertilizers is projected to reach 52.9 million tonnes by 2030, driven by the need to sustain agricultural productivity[15]. While the extensive use of chemical fertilizers over the past six decades has contributed to sufficient food production, however, this approach is increasingly recognized as economically and environmentally not a sustainable option[16,17].

In particular, the use of DAP, the second most popular fertilizer among Indian farmers after urea, has faced challenges due to raw material scarcity and rising input costs, such as rock phosphate[18]. Moreover, indiscriminate P fertilizer application contributes to environmental issues like eutrophication, as P leaches into aquatic systems[19]. Moreover, phosphorus is a finite, non-renewable resource, with some studies predicting its potential depletion within the next 50–100 years[20]. These concerns highlight the urgent need to improve phosphorus use efficiency through innovative solutions. By enhancing the effectiveness of phosphorus fertilizers and developing sustainable management strategies, it is possible to meet global wheat production targets while mitigating environmental impacts and ensuring food security for the growing population[21].

Building on the challenges posed by conventional phosphorus fertilizers and the opportunities presented by nanotechnology, this study focuses on Nano DAP as a viable solution for sustainable phosphorus management in wheat production. Nanotechnology has emerged as a promising tool to address critical challenges in agriculture, particularly the need to enhance phosphorus use efficiency (PUE) and reduce the environmental impact of conventional fertilizers. Nano-fertilizers, characterized by their high surface area and small particle size, have demonstrated the ability to improve nutrient penetration, uptake, and utilization in plants[22]. Recent studies have demonstrated that nano-fertilizers can increase photosynthetic activity, nitrogen metabolism, and overall crop productivity[23–25]. While minimizing nutrient losses and environmental pollution[26–28]. Nano DAP, a newly developed liquid fertilizer, offers a promising sustainable alternative to conventional P fertilizers. Nano DAP has the potential to reduce dependency on traditional fertilizers and save substantial foreign exchange by cutting down on imports. Estimates suggest that nano DAP, equivalent to approximately 66 lakh tonnes of conventional DAP, could save around INR 21,800 crores in subsidies each year, considering the current DAP subsidy of INR 33,000 per metric tonne[29]. These economic and sustainability benefits underscore the importance of prioritizing the development of advanced phosphate-based fertilizers and exploring alternative phosphorus sources[30]. Conventional phosphorus fertilizers face well-documented limitations, including low soil efficiency and the risk of phosphorus becoming unavailable to plants due to fixation or leaching. In contrast, phosphorus fertilizers developed using nanotechnology offer several advantages, such as enhanced nutrient use efficiency, reduced environmental risks, and improved long-term availability in the soil[31]. Studies indicate that foliar application of nano-P improves PUE and reduces nutrient losses more effectively than conventional soil application[18]. Furthermore, nano DAP provides a controlled and slow release of phosphorus, reducing leaching into groundwater and ensuring sustained nutrient availability to crops[32]. To the best of our knowledge, no systematic field studies have been reported or published that assess the relative potential of the recommended dose of P (RDP) combined with nano-DAP foliar spray application to date. In the current scenario, the application of an optimal dose of nano-fertilizer can significantly contribute to improving crop production while ensuring environmental safety, and ecological sustainability at least on a partial scale, by substituting conventional DAP through foliar application of nano DAP. To address this knowledge gap, this study was designed with the following objectives: (i) to evaluate the impact of RDP + nano DAP foliar application on the growth and yield of wheat; and (ii) to determine the effect of RDP combined with nano DAP foliar application on nutrient uptake, use efficiency, and the economic viability of wheat production (Table 1).

Materials and methods

Experimental site and experimental design

A two-year field experiment was conducted during the 2022–23 and 2023–24 cropping seasons at the ICAR–Indian Agricultural Research Institute research farm in New Delhi, India (28°39' N, 77°10' E) as depicted (Fig. 1). The site is located in a sub-tropical, semi-arid region with a climate characterized by hot, dry summers, monsoon rains (July to September), and cold winters (November to April). The area falls within the Trans-Gangetic Plains agro-climatic zone, with an average annual rainfall of 650 mm and evaporation of 850 mm (Fig. 2). Precipitation during the wheat growing season was 144.5 mm in 2022–23 and 62.0 mm in 2023–24. The experimental soil was a sandy clay loam, with 213.0 kg ha^{-1} available nitrogen (N), 8.1 kg ha^{-1} available phosphorus (P), 215.0 kg ha^{-1} exchangeable potassium (K), and 0.51% organic carbon (OC)[33].

Treatment details and field management

The experiment was conducted using a randomized complete block design with ten treatments, viz., control (zero P), 50% RDP with no spray, 50% RDP + nano DAP foliar sprays at 2.5 and 5 ml $litre^{-1}$, 75% RDP with no spray, 75% RDP + nano DAP foliar sprays at 2.5 and 5 ml $litre^{-1}$, and 100% RDP with no spray, 100% RDP + nano DAP foliar sprays at 2.5 and 5 ml $litre^{-1}$ and was replicated thrice. The nano-DAP, developed by Coromandel International Limited, contains 2% nitrogen (N) and 5% P_2O_5 with a particle size less than 100 nm[34], and two foliar applications at 20–25 DAS and 40–45 DAS were carried out in the study. The wheat variety 'HD 2967' was

Treatment details	Short forms
Zero P (control for P)	P_0
50% RDP* with no spray	P_{50}
50% RDP + Nano-DAP 2 sprays** at the rate of 2.5 ml litre^{-1}	P_{50} + $Nano_{2.5}$ ml L^{-1}
50% RDP + Nano-DAP 2 sprays at the rate of 5 ml litre^{-1}	P_{50} + $Nano_5$ ml L^{-1}
75% RDP with no spray	P_{75}
75% RDP + Nano-DAP 2 sprays at the rate of 2.5 ml litre^{-1}	P_{75} + $Nano_{2.5}$ ml L^{-1}
75% RDP + Nano-DAP 2 sprays at the rate of 5 ml litre^{-1}	P_{75} + $Nano_5$ ml L^{-1}
100% RDP with no spray	P_{100}
100% RDP + Nano-DAP 2 sprays at the rate of 2.5 ml litre^{-1}	P_{100} + $Nano_{2.5}$ ml L^{-1}
100% RDP + Nano-DAP 2 sprays at the rate of 5 ml litre^{-1}	P_{100} + $Nano_5$ ml L^{-1}

Table 1. Treatment details applied in wheat crop and respective abbreviations used throughout the text of the manuscript. RDP*, Recommended dose of phosphorus (26.2 kg P or 60 kg P_2O_5); Nano-DAP 2 sprays** (20–25 DAS and 40–45 DAS). Two foliar sprays are applied: the first at the active tillering stage and the second one week before flowering.

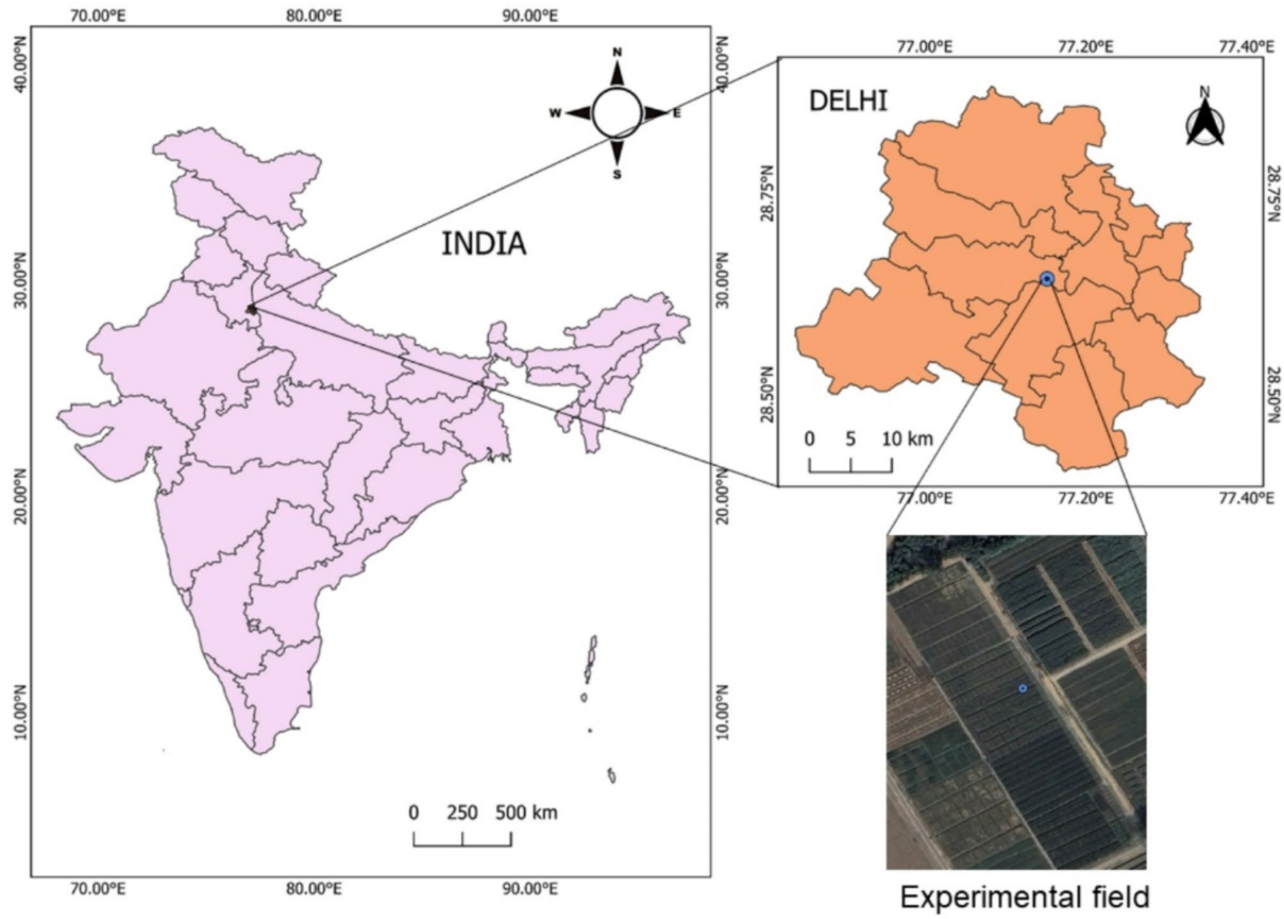

Fig. 1. Location of Experimental Field at IARI Research Farm (Map Developed Using QGIS 3.38.3).

used in both years of the experiment. To ensure uniform crop growth, sowing was performed on the same date each year with a seed rate of 100 kg ha^{-1} and a row spacing of 22.5 cm. Nutrients were applied as follows: 120 kg N ha^{-1}, 26.2 kg P ha^{-1}, and 49.8 kg potassium (K) ha^{-1}. Nitrogen was applied in three equal splits at sowing, 30 days after sowing (DAS), and 50 DAS. Potassium was applied uniformly at 49.8 kg ha^{-1}. Phosphorus application followed the respective treatment doses for both wheat growing seasons (Table 1).

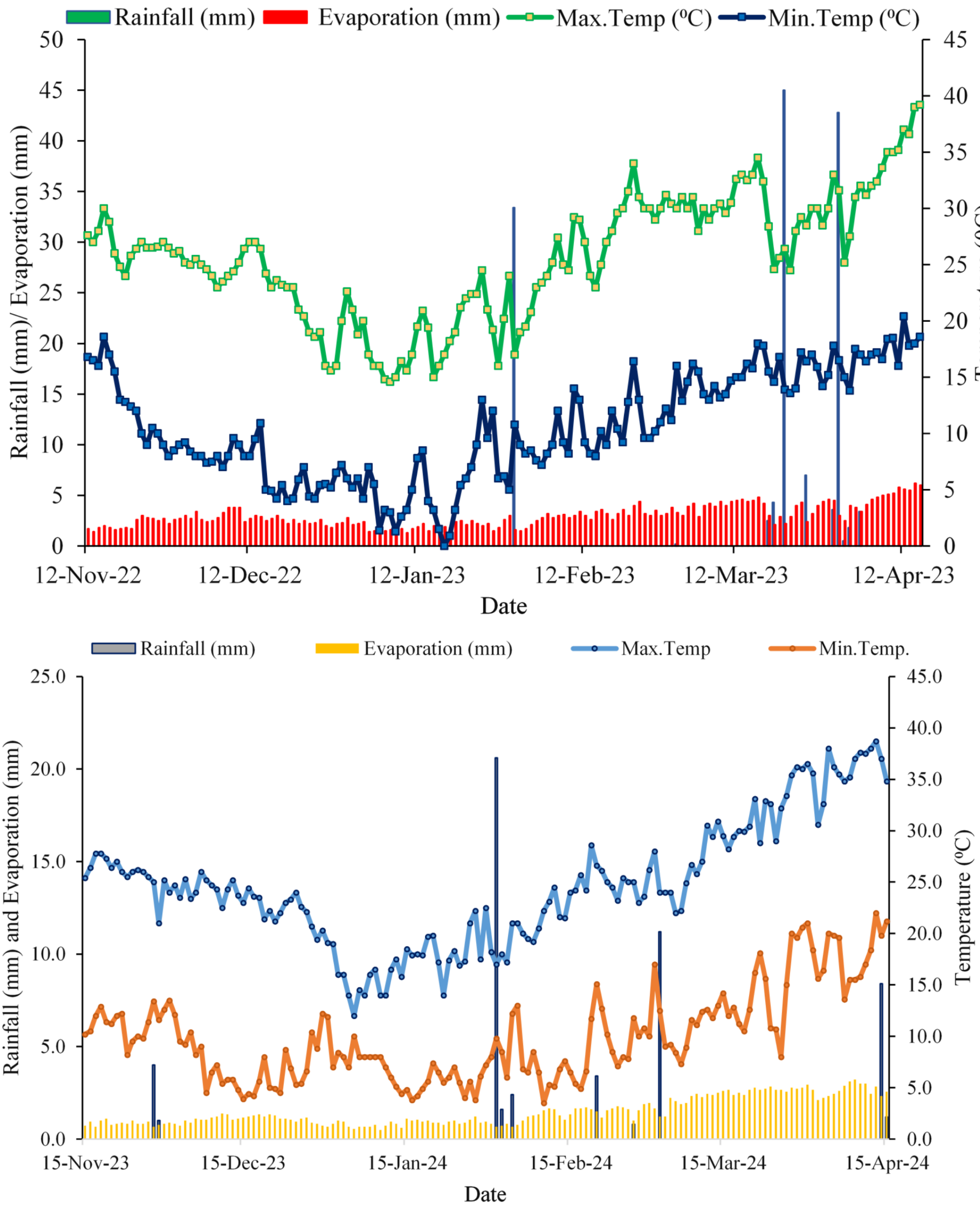

Fig. 2. Meteorological data of the experimental field during the growth period of wheat (*Rabi* season 2022–23 and 2023–24).

Sampling and analysis

Plant height was measured from the ground to the spike using a standard scale, and tillers were counted on a one-square-meter area per plot at harvest. Yield attributes were determined from a random sample of ten spikes per plot. The crop was harvested manually using sickles, beginning with the border rows, followed by the net plot area, and left to sun-dry in the field. Threshing was done manually, and grain yield was recorded at ~ 12% moisture content and expressed in t ha^{-1}. Representative grain and straw samples were collected for nutrient analysis. Samples were dried at 65 °C ± 2 °C until constant weight was achieved. Nitrogen concentration was estimated using the Kjeldahl method, and phosphorus concentration was determined using the wet di-acid digestion method with vanadomolybdophosphoric acid yellow colour[33]. Nitrogen and phosphorus uptake were calculated based on their concentrations multiplied with respective grain and straw yields. Wheat crude protein content was calculated by multiplying nitrogen concentration by a coefficient of 5.70, derived from the nitrogen content of the grain[70], and expressed as a percentage.

Nutrient use efficiency

The system partial factor productivity (PFP), agronomic efficiency (AE) for nitrogen and phosphorus, and recovery efficiency were computed using the following expressions[35,36]:

$$PFP = \frac{Grain\ yield\ of\ treated\ plot\ \left(kg\ ha^{-1}\right)}{Total\ nutrient\ applied\ \left(kg\ ha^{-1}\right)}$$

$$\text{AE} = \frac{Grain\ yield\ of\ treated\ plot\ \left(kg\ ha^{-1}\right) - Grain\ yield\ of\ control\ plot\ \left(kg\ ha^{-1}\right)}{Total\ nutrient\ applied\ \left(kg\ ha^{-1}\right)}$$

$$\text{RE}\,(\%) = \frac{Nutrient\ uptake\ in\ treated\ plot\ \left(kg\ ha^{-1}\right) - Nutrient\ uptake\ in\ control\ plot\ \left(kg\ ha^{-1}\right)}{Total\ nutrient\ applied\ (kg\ ha^{-1})} \times 100$$

Economics

Cost of cultivation was calculated by taking prevailing market prices of inputs used, interest on the capital requirement of purchases of inputs, and rental value of land. The gross return includes the cost of grain as well as the straw of wheat. Indices used for the expression of productivity and profitability were calculated as follows:

(A): $Net\ returns\ (US\ \$) = Gross\ returns\ \left(US\ \$\ ha^{-1}\right) - cost\ of\ cultivation\ \left(US\ \$\ ha^{-1}\right)$

(B): $B : C\ ratio = \frac{Net\ returns\ \left(US\ \$\ ha^{-1}\right)}{Cost\ of\ cultivation\ \left(US\ \$\ ha^{-1}\right)}$

(C): $Per\ day\ profitability\ (US\ \$\ day - 1\ ha^{-1}) = \frac{Net\ returns\ \left(US\ \$\ ha^{-1}\right)}{Duration\ of\ cropping\ system\ (days)}$

Data analysis

Data of all parameters was analyzed statistically by performing an analysis of variance (ANOVA). The least significant difference (LSD) at $P = 0.05$ was used to determine significant differences between treatment means. Bar plot figures were generated using Microsoft Excel (2007). Boxplots and Pearson correlation plots were created using the ggplot, GGally, and ggcorrplot packages in RStudio (R Core Team, 2013).

Authors have confirmed that all the plant studies were carried out in accordance with relevant national, international or institutional guidelines.

Results

Growth parameters of wheat

Data indicates that the growth of wheat, as measured by plant height and the number of tillers per square meter, was significantly ($p \le 0.05$) enhanced by the application of nano DAP as presented in Table 2. All levels of 75% RDP combined with nano DAP (5 ml L^{-1}) showed a stimulatory effect on wheat growth, comparable to the 100% RDP treatment with and without spray. The two years of experimentation showed that the application of 100% RDP + nano DAP foliar spray at 5 ml L^{-1}, increased the grains spike^{-1}, and grain-weight spike^{-1}. However,

Treatment	Plant height (cm)		Tillers m^{-2}	
	2022–23	2023–24	2022–23	2023–24
P_0	92.5^{c}	90.3^{c}	412^{g}	415^{f}
P_{50}	94.3^{bc}	92.4^{bc}	420^{fg}	423^{ef}
P_{50} + $Nano_{2.5}$ ml L^{-1}	95.6^{abc}	92.8^{abc}	426^{ef}	425^{e}
P_{50} + $Nano_{5}$ ml L^{-1}	96.2^{abc}	93.5^{abc}	432de	428de
P_{75}	95.2^{abc}	93.8^{ab}	422^{f}	425^{e}
P_{75} + $Nano_{2.5}$ ml L^{-1}	96.7^{ab}	94.2^{ab}	443^{c}	436^{d}
P_{75} + $Nano_{5}$ ml L^{-1}	97.3^{ab}	94.8^{ab}	447^{bc}	448^{c}
P_{100}	96.3^{abc}	95.3^{ab}	442^{c}	461^{b}
P_{100} + $Nano_{2.5}$ ml L^{-1}	97.2^{ab}	95.7^{ab}	452^{ab}	465^{ab}
P_{100} + $Nano_{5}$ ml L^{-1}	98.5^{a}	96.2^{a}	460^{a}	470^{a}
LSD ($p = 0.05$)	3.48	1.02	8.01	8.25

Table 2. Growth parameters of wheat under different levels of phosphorus in conjunction with nano DAP application. Values represent means from three replicates. Mean values followed by different letters are significantly different at $p = 0.05$ using Tukey's honestly significant difference test.

the most substantial growth improvements were observed with the P_{100} + $nano_5$ ml L^{-1}, which was statistically on par with the P_{100} treatment. The application of P_{100} + $nano_5$ ml L^{-1} resulted in a 6.5% increase in plant height and an 18.8% increase in the number of tillers per square meter during 2022–23, and a 6.5% and 13.6% increase, respectively, in 2023–24, compared to zero P application (Table 2). However, P_{75} + nano remained on par with P_{100} treatments in all parameters. This improvement was attributed to enhanced wheat growth under the P_{75} + nano treatment. Similarly, the P_{75} + $nano_5$ ml L^{-1} treatment resulted in increases in plant height, and the number of tillers per square meter by 5.2%, 12.5% in 2022–23, and by 5.0%, 8.6% in 2023–24, respectively, compared to control (Figs. 1 and 2).

Yield attributes and yields of wheat

Application of nano DAP along with 100% RDP resulted in a significant ($p \leq 0.05$) increase in the yield attributes, including the number of grains $spike^{-1}$ and the grain-weight $spike^{-1}$, as well as grain yield, straw yield, and biological yield, compared to the control. All measured yield parameters showed significant ($p \leq 0.05$) improvement in response to nano DAP, with the best results observed in the P_{100} + $nano_5$ ml L^{-1}. Notably, when the phosphorus application was reduced by 25%, the P_{75} + $nano_5$ ml L^{-1} produced yield attributes comparable to the P_{100} treatment. Specifically, with the P_{75} + $nano_5$ ml L^{-1} treatment, the number of grains $spike^{-1}$ and grain-weight $spike^{-1}$ increased by 16.3% and 6.0% in 2022–23 and by 18.2% and 4.4% in 2023–24, respectively, over the control (Table 3). Grain and straw yields also differed significantly among the phosphorus-applied treatments. Treatments involving different levels of phosphorus, particularly P_{100} + $nano_5$ ml L^{-1}, recorded significantly higher grain and straw yields compared to treatments receiving P_{50} + nano DAP foliar sprays. P_{75} + $nano_5$ ml L^{-1} treatment resulted in grain and straw yields that were comparable to the P_{100} treatment, showing increases of 23.2% and 17.1% in 2022–23, and 10.8% and 10.4% in 2023–24, respectively, compared to the zero P application. However, these yield parameters increased by up to 34.8% and 27.5% in 2022–23, and by 14.7% and 12.9% in 2023–24, respectively, with the P_{100} + $nano_5$ ml L^{-1} treatment, as compared to no P application (Table 4). Grain yields in 2023, P_{50} + $nano_{2.5}$ ml L^{-1} resulted in a 13.7% reduction in yields, while P_{50} + $nano_5$ ml L^{-1} showed a 7.8% decrease compared to P_{100}. However, straw yields in 2023, resulted in a decrease to the tune of 10.6% and 2.8% with P_{50} + $nano_{2\cdot 5}$ ml L^{-1}. In 2024, both treatments achieved similar grain and straw yields comparable to P_{100}. With the increase of RDP, the thousands grain weight (TGW) increased; however, there was no significant difference between treatments. A pooled analysis of grain yield (Fig. 3) indicated significant differences between the years of study with respect to the treatments applied. In contrast, the pooled analysis of straw yield (Fig. 4) showed no significant differences between the years of experimentation.

Phosphorus, nitrogen contents, and their uptake by wheat

Data on the effect of nano DAP foliar sprays combined with varying rates of recommended dose of phosphorus demonstrated that nano DAP foliar sprays, as compared to no spray, were highly effective in enhancing both straw and grain phosphorus and nitrogen concentrations. The application of P_{100} + $nano_5$ ml L^{-1} resulted in significantly higher ($p < 0.05$) straw and grain P concentrations compared to the P_{50} + $nano_5$ ml L^{-1} treatment. The highest P concentrations in straw and grain were observed with the P_{100} + $nano_5$ ml L^{-1} treatment, where the grain P concentration was 0.52% and straw P concentration was 0.18% in 2022–23, and 0.42% and 0.17% in 2023–24, respectively as shown (Fig. 5). Additionally, the N content in grain and straw increased to 2.15% and 0.68% in 2022–23 and 2.11% and 0.65% in 2023–24, respectively, with the P_{100} + $nano_5$ ml L^{-1} (Fig. 6). Similarly, the application of nano DAP significantly increased nutrient uptake in both straw and grain (Table 5). Phosphorus uptake in straw and grain under the P_{100} + $nano_5$ ml L^{-1} was 24.0 kg ha^{-1} and 17.4 kg ha^{-1} in 2022–23, and 26.3 kg ha^{-1} and 15.1 kg ha^{-1} in 2023–24, respectively. Nitrogen uptake by grain and straw increased to 100.0 kg ha^{-1} and 65.6 kg ha^{-1} in 2022–23, and 131.9 kg ha^{-1} and 57.8 kg ha^{-1} in 2023–24, respectively, under

Treatment	Spike length (cm)		Grains $spike^{-1}$		Grain weight (g) $spike^{-1}$		1000-grain weight (g)	
	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24
P_0	8.0^{c}	8.1^{g}	43^{c}	44^{e}	1.84^{d}	1.81^{e}	38.1^{e}	38.6^{c}
P_{50}	8.1^{c}	8.2^{fg}	48^{b}	48^{d}	1.90^{c}	1.84^{de}	39.5^{d}	39.6^{bc}
P_{50} + $Nano_{2.5}$ ml L^{-1}	8.5^{bc}	8.4^{efg}	49^{b}	49^{cd}	1.93^{bc}	1.85^{d}	40.2^{bc}	40^{abc}
P_{50} + $Nano_5$ ml L^{-1}	8.7^{abc}	8.5^{def}	50^{ab}	50^{bcd}	1.95^{b}	1.87^{cd}	40.5^{ab}	40.3^{ab}
P_{75}	8.5^{bc}	8.5^{def}	48^{b}	48^{d}	1.91^{c}	1.84^{de}	40.1^{bc}	40.1^{ab}
P_{75} + $Nano_{2.5}$ ml L^{-1}	8.7^{abc}	8.7^{cde}	49^{b}	51^{abcd}	1.93^{bc}	1.87^{cd}	40.5^{ab}	40.8^{ab}
P_{75} + $Nano_5$ ml L^{-1}	9.0^{ab}	8.8^{bcd}	50^{ab}	52^{abc}	1.95^{b}	1.89^{bc}	40.7^{a}	41.0^{ab}
P_{100}	9.1^{ab}	8.9^{abc}	49^{b}	52^{abc}	1.93^{bc}	1.89^{bc}	39.8^{cd}	41.1^{ab}
P_{100} + $Nano_{2.5}$ ml L^{-1}	9.3^{ab}	9.1^{ab}	50^{ab}	53^{ab}	1.95^{b}	1.92^{ab}	40.3^{b}	41.3^{a}
P_{100} + $Nano_5$ ml L^{-1}	9.5^{a}	9.2^{b}	52^{a}	54^{a}	2.15^{a}	1.94^{a}	40.8^{a}	41.5^{a}
LSD ($p = 0.05$)	0.84	0.31	2.85	2.86	0.04	0.03	0.43	1.35

Table 3. Yield attributes of wheat under different levels of phosphorus in conjunction with nano DAP application. Values represent means from three replicates. Mean values followed by different letters are significantly different at $p = 0.05$ using Tukey's honestly significant difference test.

Treatmetn	Grain yield (t ha^{-1})		Straw yield (t ha^{-1})		Harvest index (%)	
	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24
P_0	3.45^{g}	5.45^{f}	7.56^{f}	7.87^{g}	31.84	40.91
P_{50}	3.65^{fg}	5.68^{e}	7.82^{ef}	8.15^{fg}	32.15	41.07
P_{50} + $Nano_{2.5}$ ml L^{-1}	3.85^{ef}	5.86^{cde}	8.12^{de}	8.36^{def}	32.16	41.21
P_{50} + $Nano_5$ ml L^{-1}	3.96^{de}	5.93^{bcd}	8.35^{cd}	8.48^{bcde}	32.04	41.16
P_{75}	3.84^{ef}	5.75^{de}	8.14^{de}	8.24^{ef}	32.42	41.10
P_{75} + $Nano_{2.5}$ ml L^{-1}	4.16^{bcd}	5.95^{bcd}	8.67^{bc}	8.56^{bcd}	32.47	40.92
P_{75} + $Nano_5$ ml L^{-1}	4.25^{bc}	6.04^{abc}	8.85^{b}	8.69^{abc}	32.42	41.01
P_{100}	4.15^{cd}	5.85^{cde}	8.65^{bc}	8.38^{cdef}	32.49	41.10
P_{100} + $Nano_{2.5}$ ml L^{-1}	4.36^{b}	6.13^{ab}	9.06^{b}	8.75^{ab}	32.53	41.20
P_{100} + $Nano_5$ ml L^{-1}	4.65^{a}	6.25^{a}	9.64^{a}	8.89^{a}	31.84	41.28
LSD (p = 0.05)	0.21	0.22	0.42	0.32	NS	NS

Table 4. Grain and straw yields of wheat under different levels of phosphorus in conjunction with nano DAP application. Values represent means from three replicates. Mean values followed by different letters are significantly different at p = 0.05 using Tukey's honestly significant difference test.

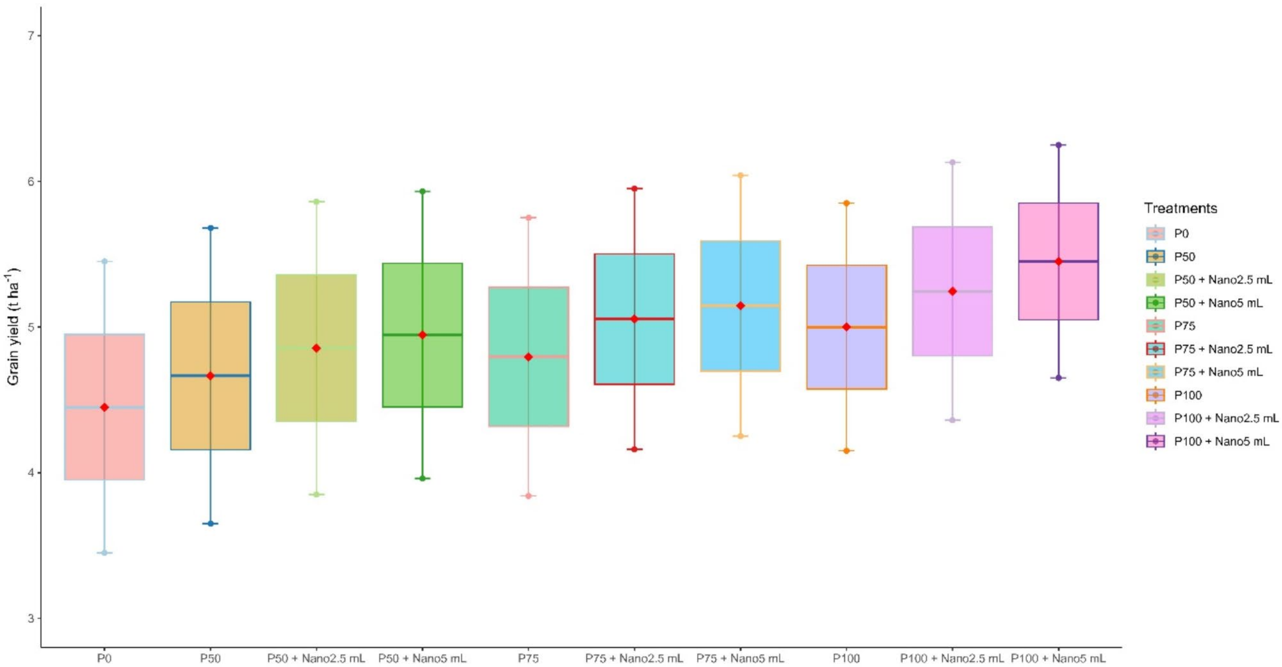

Fig. 3. Pooled analysis of grain yield under different phosphorus levels and nano DAP application during two years of study. Treatment details are described in detail in the materials and methods section (mL may be referred to as milli litres $litre^{-1}$).

the same treatment. However, the pooled analysis of P uptake (Fig. 7) showed no significant differences between the years of experimentation.

Phosphorus use efficiency by wheat

The partial factor productivity (PFP), agronomic use efficiency (AE), and recovery efficiency (RE) varied significantly among the treatments (Table 6). The agronomic efficiency (AE) of phosphorus was recorded as 7.89 and 15.87 kg of grain increase kg^{-1} of P applied in the P_{50} + $nano_5$ ml L^{-1} during 2022–23 and 2023–24, respectively. Similarly, the AE of nitrogen was 3.89 kg and 7.99 kg of grain increase kg^{-1} of N applied in the P_{50} + $nano_5$ ml L^{-1}. However, the highest AE for phosphorus and nitrogen was observed in the P_{100} + $nano_5$ ml L^{-1} treatment, with 19.92 kg of grain increase kg^{-1} of P applied and 9.21 kg of grain increase kg^{-1} of N applied in 2022–23 as depicted (Fig. 8). Recovery efficiency varied, ranging from 4.0 to 16.4% as the treatments increased from P_{50} to P_{100} + $nano_5$ ml L^{-1} in 2022–23, and from 10.3 to 23.6% as the treatments increased from $P_{50}$to P_{100} + $nano_5$ ml L^{-1} in 2023–24 (Table 6). The PFP was significantly higher in treatments with 50% RDP compared to those with 100% RDP, and it was further enhanced with the application of nano DAP. Specifically,

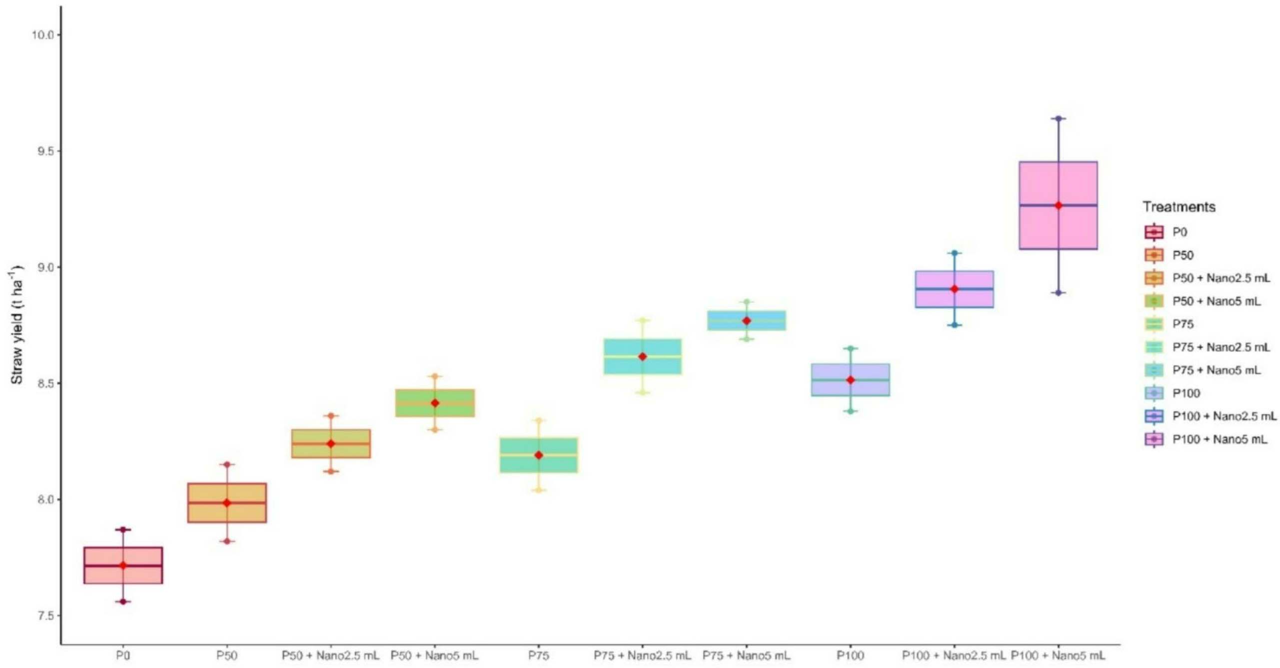

Fig. 4. Pooled analysis of straw yield under different phosphorus levels and nano DAP application during two years of study (mL may be referred to as milli litres litre^{-1}).

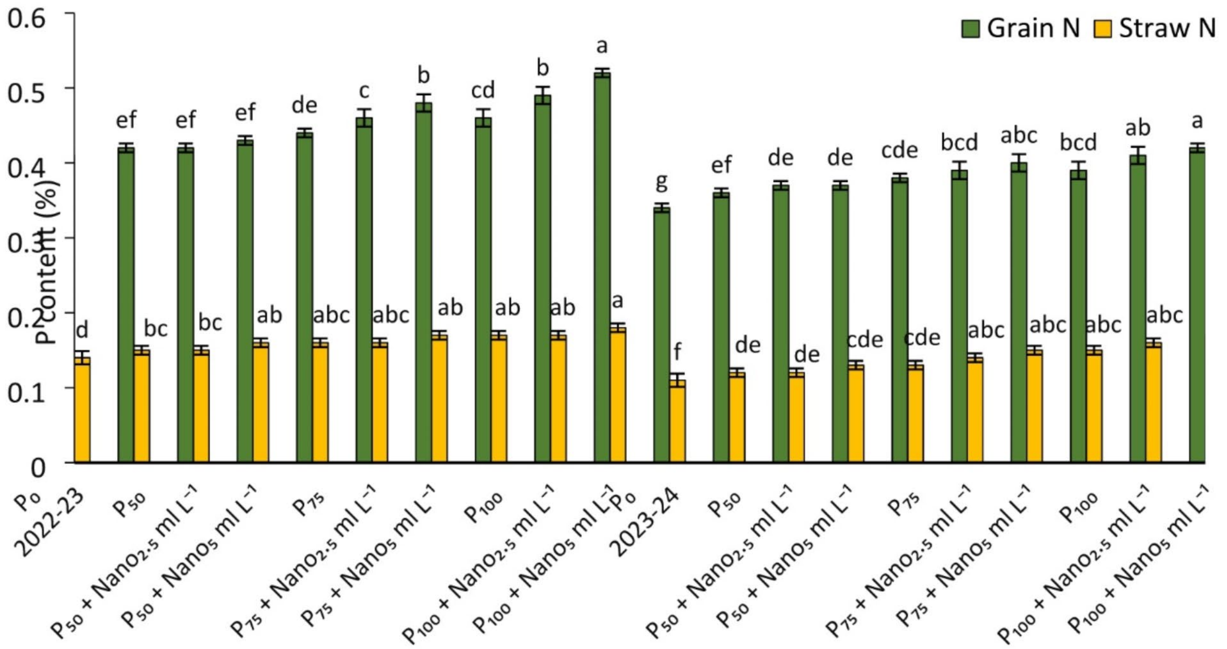

Fig. 5. Effect of different levels of phosphorus in conjunction with nano DAP application on phosphorus contents of wheat grain and straw.

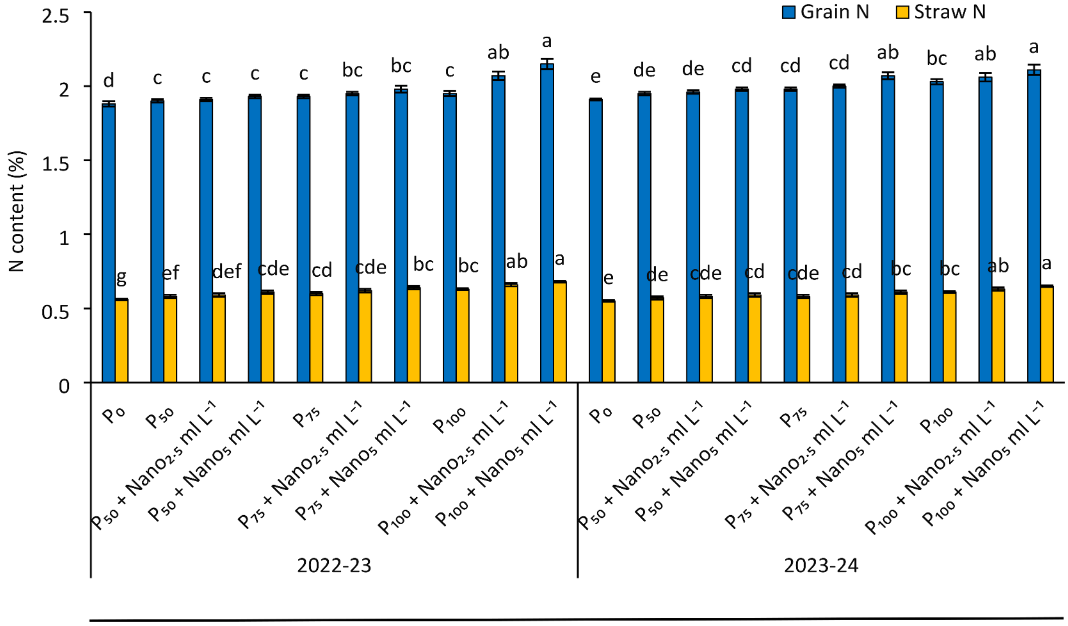

Fig. 6. Effect of different levels of phosphorus in conjunction with nano DAP application on nitrogen contents of wheat grain and straw.

Treatment	*N* uptake (kg ha^{-1})				*P* uptake (kg ha^{-1})			
	Grain		Straw		Grain		Straw	
	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24
P_0	64.88^{g}	104.10^{e}	42.33^{g}	43.30^{f}	14.13^{f}	18.50^{f}	10.57^{g}	8.70^{e}
P_{50}	69.40^{fg}	110.80^{d}	45.36^{fg}	46.50^{ef}	15.34^{e}	20.50^{ef}	11.70^{fg}	9.80^{de}
P_{50} + $Nano_{2.5}$ ml L^{-1}	73.56^{ef}	113.57^{cd}	47.94^{ef}	48.50^{de}	16.16^{de}	21.70^{de}	12.19^{efg}	10.00^{de}
P_{50} + $Nano_5$ ml L^{-1}	76.37^{de}	115.03^{cd}	50.89^{de}	50.00^{cd}	17.07^{d}	21.90^{cde}	13.35^{cdef}	11.00^{cd}
P_{75}	74.08^{ef}	113.90^{cd}	48.87^{ef}	47.80^{de}	16.90^{d}	21.90^{cde}	12.93^{def}	10.70^{cd}
P_{75} + $Nano_{2.5}$ ml L^{-1}	81.08^{cd}	118.60^{c}	53.75^{cd}	50.50^{cd}	19.13^{c}	23.10^{bcd}	13.85^{bcde}	12.00^{bc}
P_{75} + $Nano_5$ ml L^{-1}	84.23^{bc}	125.00^{b}	56.62^{bc}	53.00^{bc}	20.41^{b}	24.20^{abc}	14.96^{bc}	13.00^{b}
P_{100}	80.90^{cd}	118.80^{c}	54.43^{cd}	51.10^{cd}	19.00^{cd}	22.80^{bcde}	14.70^{bcd}	12.60^{b}
P_{100} + $Nano_{2.5}$ ml L^{-1}	90.27^{b}	126.30^{b}	59.80^{b}	55.10^{ab}	21.36^{b}	25.10^{ab}	15.39^{b}	13.10^{b}
P_{100} + $Nano_5$ ml L^{-1}	100.04^{a}	131.90^{a}	65.56^{a}	57.80^{a}	24.01^{a}	26.30^{a}	17.35^{a}	15.10^{a}
LSD (p = 0.05)	6.50	5.27	3.74	3.39	1.08	2.21	1.80	1.42

Table 5. Nitrogen and phosphorus uptake of wheat under different levels of phosphorus in conjunction with nano DAP application. Values represent means from three replicates. Mean values followed by different letters are significantly different at p = 0.05 using Tukey's honestly significant difference test.

the PFP in the P_{50} + $nano_5$ ml L^{-1} treatment was superior to the same treatment without foliar nano-DAP spray, underscoring the role of nano-DAP in improving PFP. Additionally, the P_{100} + $nano_5$ ml L^{-1} treatment performed similarly to the P_{100} treatment without nano-DAP spray in terms of use efficiencies.

Economics analysis of wheat: costs and returns

During both the study years, the cost of cultivation was highest in the treatment P_{100} + $nano_5$ ml L^{-1} treatment, with costs of (US $ 889.0 ha^{-1}) and (US $ 896.9 ha^{-1}) in 2022–23 and 2023–24, respectively. This was followed closely by the P_{100} + $nano_{2.5}$ ml L^{-1} treatment at (US $ 881.0 ha^{-1}) and (US $ 887.8 ha^{-1}) in 2022–23 and 2023–24, respectively. The lowest cultivation cost was recorded in the control treatment with zero P (Table 7). The application of nano-DAP with 2 sprays increased the overall cultivation cost of the wheat crop. However, this increase was justified by the improvements in yields and net returns, which outweighed the additional expenses. The higher gross returns were observed in the second year compared to the first year due to increased yields. The gross returns were (US $ 1,834.2 ha^{-1}) and (US $ 2,061.9 ha^{-1}) in 2022–23 and 2023–24, respectively. Net returns were (US $ 958.6 ha^{-1}) in 2022–23 and (US $ 1,197.1 ha^{-1}) in 2023–24 for the P_{75} + $nano_5$ ml L^{-1}. This treatment was performed on par with the 100% RDP treatment without spray. However, the highest gross returns were recorded in the P_{100} + $nano_5$ mL^{-1} treatment, with (US $ 1,929.6 ha^{-1}) in 2022–23 and (US $ 2,128.7 ha^{-1}) in

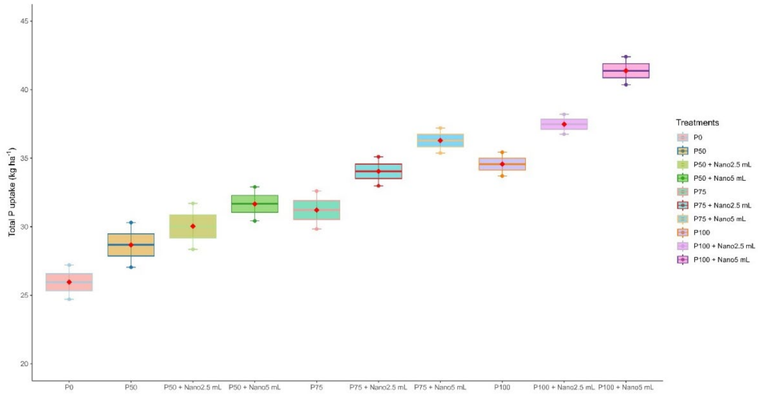

Fig. 7. Pooled analysis of total P uptake under different phosphorus levels and nano DAP application during two years of study (mL may be referred to as milli litres litre^{-1}).

Treatments	Crude protein (%)		PFP (kg grain kg^{-1}*P* applied)		RE (%)	
	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24
P_0	10.10^c	10.26^b	–	–	–	–
P_{50}	10.20^{bc}	10.47^b	121.77^b	189.33^b	4.01^f	10.33^c
P_{50} + $Nano_{2.5}$ ml L^{-1}	10.26^{bc}	10.53^{ab}	127.80^a	194.50^a	6.19^{ef}	14.93^{bc}
P_{50} + $Nano_5$ ml L^{-1}	10.36^b	10.64^a	130.79^a	196.00^a	9.51^{cd}	18.83^{abc}
P_{75}	10.37^b	10.63^a	85.33^d	127.77^d	6.13^{ef}	12.00^c
P_{75} + $Nano_{2.5}$ ml L^{-1}	10.46^b	10.74^a	92.18^c	131.40^{cd}	11.07^{bc}	17.50^{abc}
P_{75} + $Nano_5$ ml L^{-1}	10.63^a	11.12^a	94.00^c	133.50^c	13.86^{ab}	22.10^{ab}
P_{100}	10.47^b	10.90^a	69.17^f	97.50^f	8.10^{de}	13.73^{bc}
P_{100} + $Nano_{2.5}$ ml L^{-1}	11.12^a	11.06^a	72.51^f	101.97^{ef}	12.01^{bc}	18.30^{abc}
P_{100} + $Nano_5$ ml L^{-1}	11.55^a	11.33^a	77.18^e	103.70^e	16.37^a	23.57^a
LSD (p = 0.05)	0.93	0.84	4.52	4.67	2.79	8.54

Table 6. Crude protein, partial factor productivity (PFP) and recovery efficiency (RE) of phosphorous in wheat under different levels of phosphorus in conjunction with nano DAP application. Values represent means from three replicates. Mean values followed by different letters are significantly different at $p = 0.05$ using Tukey's honestly significant difference test.

2023–24. The net returns for this treatment were (US $ 1,022.3 ha^{-1}) in 2022–23 and (US $ 1,248.9 ha^{-1}) in 2023–24 (Table 7). The increase in net returns was highly influenced by the increase in yield. However, the use of P_{50} + $nano_5$ ml L^{-1} and $nano_{2.5}$ ml L^{-1} reduced net returns by 7.8% and 1.5% in the first year, and by 10.6% and 6.0% in the second year, respectively, compared to P_{100}. The highest net B: C ratio of wheat was 1.39 in 2022–23 and 1.42 in 2023–24 with the application P_{100} + $nano_5$ ml L^{-1}, while the lowest net B-C ratio was observed in the control treatment. The highest per-day profitability was observed with the application of P_{100} + $nano_5$ ml L^{-1} treatment (US $ 6.7 and US $ 14.7 ha^{-1} day^{-1}) during both study years (Fig. 9).

Correlation analysis of different wheat traits

Correlation coefficients were calculated between yields, yielding traits (grains spike^{-1}, grain weight spike^{-1}), and uptake of P and N in grain and straw. Significant positive correlation ($p < 0.001$) between the total nitrogen uptake and the nitrogen content in grain and straw, as observed during both years. Plant height measured had a strong positive correlation with grain yield ($r = 0.86$; $p < 0.001$), and straw yield ($r = 0.90$; $p < 0.001$). Grain yield was also positively correlated with grains spike^{-1} ($r = 0.94$; $p < 0.001$) and tillers number ($r = 0.80$; $p < 0.001$). The correlation between grain yield and RE was also significant, but the strength of the correlation varied depending on the combinations of phosphorus supplied through conventional DAP. These findings suggest that the growth parameters and the yield attributes have a direct impact on the grain yield and play a significant role in determining the grain yield. The relationship among all different yielding traits, yield, P and N uptake, and content were analyzed to build a Pearson correlation graph (Fig. 10).

Discussion

Nanotechnology offers promising solutions to address the low phosphorus availability typically associated with conventional phosphate fertilizers[32]. This approach offers several benefits, including enhanced absorption, improved photosynthesis through leaf surface coverage, and controlled nutrient release[18,37], nano-fertilizers

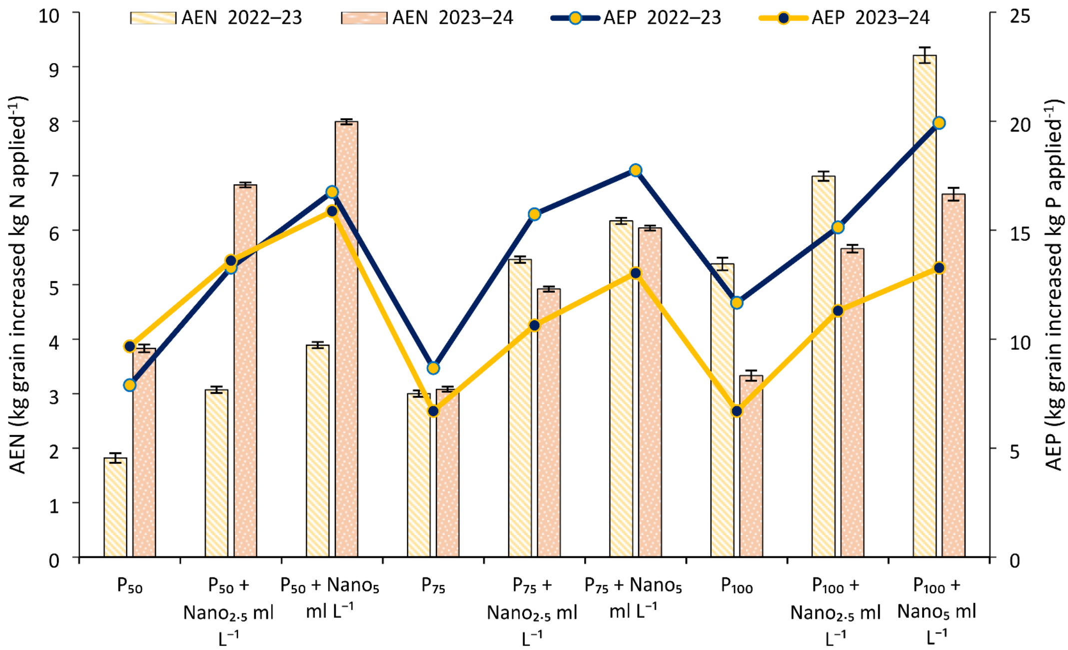

Fig. 8. Effect of different levels of phosphorus in conjunction with nano DAP application on nitrogen and phosphorus agronomic efficiency.

Treatments	Cost of cultivation (US \$ ha^{-1} year^{-1})		Gross returns (US \$ ha^{-1} year^{-1})		Net returns (US \$ ha^{-1} year^{-1})		Benefit-cost ratio	
	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24
P_0	811.3	816.7	1565.2^f	1861.9^f	784.8^d	1024.1^f	1.01^e	1.22^{bc}
P_{50}	831.7	838.0	1714.4^{de}	1938.0^e	876.4^{de}	1073.2^{ef}	1.05^{cd}	1.24^{bc}
P_{50} + $Nano_{2.5}$ ml L^{-1}	862.3	866.5	1766.1^{de}	1997.1^{cde}	899.6^{de}	1121.0^{cde}	1.04^{cd}	1.28^b
P_{50} + $Nano_5$ ml L^{-1}	871.5	875.6	1725.9^{de}	2021.9^{bcd}	919.3^{cd}	1173.9^{abcd}	1.05^{cd}	1.39^{abc}
P_{75}	840.2	848.7	1751.7^{ef}	1961.4^{de}	923.0^d	1100.0^{def}	1.06^{cd}	1.28^b
P_{75} + $Nano_{2.5}$ ml L^{-1}	871.7	877.2	1824.1^{bcd}	2025.7^{bcd}	947.1^{bc}	1153.4^{bcde}	1.08^c	1.32^{abc}
P_{75} + $Nano_5$ ml L^{-1}	880.7	886.2	1834.2^{bc}	2061.9^{abc}	958.6^b	1197.1^{abc}	1.08^c	1.39^{abc}
P_{100}	852.4	859.3	1908.4^{cd}	1995.3^{cde}	969.7^b	1137.5^{bcde}	1.11^b	1.33^{abc}
P_{100} + $Nano_{2.5}$ ml L^{-1}	881.1	887.8	1916.0^b	2089.3^{ab}	986.9^b	1221.1^{ab}	1.11^b	1.41^{ab}
P_{100} + $Nano_5$ ml L^{-1}	889.0	896.9	1929.6^a	2128.7^a	1022.3^a	1248.9^a	1.14^a	1.42^a
LSD (p = 0.05)	–	–	4.603	6.225	4.603	6.225	0.06	0.16

Table 7. Economics of wheat under different levels of phosphorus in conjunction with nano DAP application. Values represent means from three replicates. Mean values followed by different letters are significantly different at p = 0.05 using Tukey's honestly significant difference test. 1 US \$ = 82.50 INR (2022–23); 83.50 INR (2023–24).

can boost crop production[38], optimize phosphorus usage, and improve the effective absorption of nutrients[39]. Applying nano-fertilizers *via* foliar spraying allows them to penetrate plants either through the epidermis or stomata, subsequently moving through the apoplast or symplast[40]. To enhance phosphorus use efficiency and boost agricultural productivity, nano-sized phosphorus fertilizers are being developed. These fertilizers have the potential to increase plant yield, enhance nutrient use efficiency, and minimize environmental impacts[24,41,42]. Foliar application of phosphorus has shown greater utilization efficiency compared to soil application, and when combined with soil-applied phosphorus, it can further improve phosphorus use efficiency[43].

The results of our study showed the significant impact of nano DAP on enhancing the growth and yield of wheat. Application of nano DAP resulted in increased plant height, spike length, grains spike^{-1}, as well as higher grain and straw yields. A key factor behind these improvements was the consistent and prolonged supply of phosphorus provided by nano DAP throughout the wheat growth period. Unlike conventional DAP, nano DAP offers a more sustained release of phosphorus, thereby supporting plant growth more effectively[6,18]. Furthermore, nano DAP effectively met the immediate nitrogen and phosphorus requirements, which activated enzymatic activities and protein assimilation pathways, thereby enhancing biomass production and mean crop growth

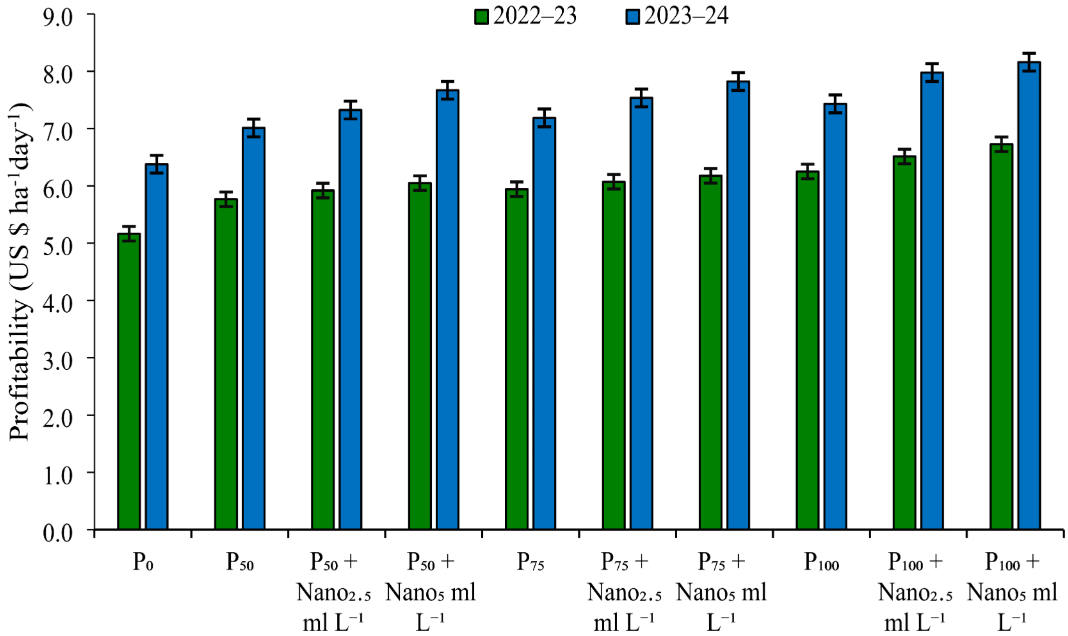

Fig. 9. Effect of different levels of phosphorus in conjunction with nano DAP application on profitability earned during cropping season.

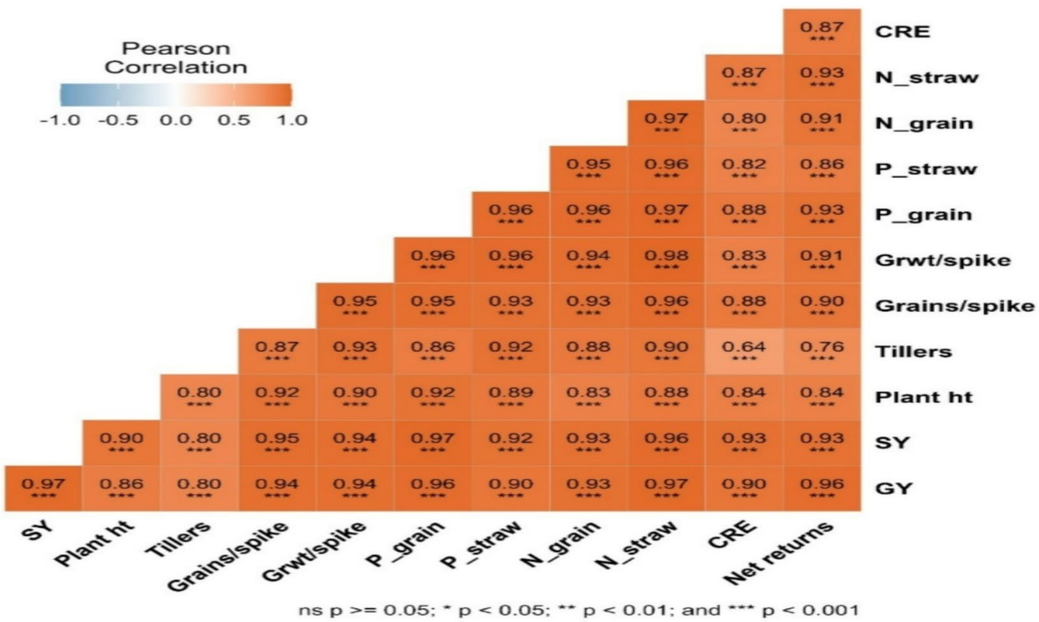

Fig. 10. Pearson's correlation among different parameters of wheat genotypes under different levels of phosphorus application. The correlation coefficient (r values) was calculated from the mean of two years' data from 2020–21 to 2021–22. *** = significance at $p < 0.001$, ** = significance at $p < 0.01$ and * = $p < 0.05$, respectively. grain yield (GY); straw yield (SY); plant height at harvest (Plant ht); tillers/m^2 (Tillers) grain weight/spike (Grwt/spike); phosphorus uptake by grain (P_grain); phosphorus uptake by straw (P_straw); nitrogen uptake by grain (N_grain); nitrogen uptake by straw (N_straw); recovery efficiency (CRE).

rate[44]. These findings are consistent with those of Singh et al.[45] who also observed significant improvements in crop performance with nano DAP. The combined application of nano DAP with the recommended dose of phosphorus has been shown to significantly enhance the growth and yield of various crops[25,46,47]. The uptake of phosphorus by crops can be further optimized by minimizing its reaction with soil constituents and enhancing its absorption through the foliar application of nano DAP[48]. Our study found that the foliar application of nano DAP not only improved the growth and yield of wheat but also demonstrated an increasing trend in all growth and yield attributing characters with higher levels of phosphorus 100% RDP + nano DAP foliar spray (Table 4). In particular, grain yields were higher in the second year of the experiment compared to the first, likely due to more favourable weather conditions that supported optimal growth[49], suggesting that nano DAP is particularly effective under optimal environmental conditions. The variation observed in the growth, yield attributes, and yield of the two years can be attributed to the weather variation, mainly in terms of rainfall (Fig. 2). From our results, it is evident that nano-P, a form of phosphorus in nano DAP, demonstrated the ability to save 25% of the recommended phosphorus dose while maintaining wheat crop yields at levels comparable to the 100% recommended dose of DAP[18]. Foliar application has emerged as a viable strategy for increasing nutrient availability to crops, leading to improved yield, yield components, and biomass production, even with reduced fertilizer inputs[45,50]. This efficiency is largely due to nano-P's ability to penetrate the plant cuticle and move through the vascular system more effectively than conventional phosphorus forms[40]. A previous study observed increases of 44.6% in grain yields and 13.1% in straw yields following the application of nano fertilizers, likely due to enhanced growth hormone activity, metabolic processes, and photosynthetic efficiency[51]. Compared to soil fertilizer applications, foliar fertilization proved more effective under various environmental conditions, as it delivers nutrients directly to the leaves, allowing for quicker absorption and reducing dependence on root activity and soil water availability[52]. These findings align with previous studies, where the application of nano-P through DAP was shown to enhance nutrient availability and uptake, leading to increased leaf area, dry matter accumulation, and improved metabolic processes, ultimately boosting wheat yield and growth metrics[53–55]. The sustained release and improved absorption of phosphorus in nano-P form are likely responsible for the increased photosynthetic rate and biomass yield accumulation observed in this study[56]. Similar benefits of nano-fertilizers have been reported in other crops, further supporting their potential as a smart agricultural practice[39,57,58]. These results highlight the promise of nano DAP foliar spray as a sustainable and efficient alternative to conventional fertilizers in enhancing wheat production.

Nutrient uptake is intrinsically connected to both yield and the concentration of nutrients within plants. In this study, significant variations in uptake values were observed, which were largely influenced by the differences in grain and straw yields across the treatments. The application of the 100% RDP combined with nano DAP led to a significant increase in the uptake of P and N by the plants, a portion of which was translocated to the grains (Table 5). The higher uptake in wheat grain was mainly governed by higher P concentration in grain[59]. This increase can be attributed to the higher grain yields, as well as the improved nutrient content, which likely resulted from enhanced soil fertility and greater nutrient availability to the crop. In the second year of the experiment, nitrogen and phosphorus uptake by plants increased compared to the first year, particularly in treatments with high recommended doses, which was reflected in the higher yields recorded during the second year. As observed in our study, the increase in P concentration following the application of nano-P is likely due to the small particle size (25–50 nm), which increases the total surface area, aiding in the retention of P and protecting it from fixation. This mechanism results in a controlled release of nutrients, making phosphorus available to the plant over an extended period[60]. Nano-P also augmented P content in both straw and grain, which can be attributed to higher phosphorus uptake due to its increased availability throughout the growing season, aligning with the plant requirement[55]. The treatment with 100% RDP combined with nano DAP sprays resulted in higher nutrient uptake, aligning with the findings of Kaviani et al.[61] who reported that foliar-applied nano-P significantly enhanced N, P, and K concentrations in treated plants compared to the controls. Dhansil et al.[60] similarly reported that the use of nano fertilizers increased phosphorus content in the straw and grain of pearl millet. N and P nutrition in wheat plants is an important aspect[62]. Additionally, Soliman et al.[63] identified a positive relationship between P and N uptake, noting that as P intake increases, N uptake rises correspondingly. Likewise, the application of nano-P fertilizer increased phosphorus uptake in broad beans by 6.7% in the straw and 5.24% in the grains[55]. The concentration in grain was 4.6–4.8 times higher than that of straw which, might be due to the translocation of P from straw to wheat grain[59]. Therefore, reducing phosphorus application by 25% while using 75% RDP + nano DAP foliar sprays can be an effective strategy. This approach maintains nutrient concentrations and uptake comparable to those achieved with 100% RDP, consistent with the findings reported[18].

Nutrient use efficiency typically declines as fertilizer doses increase due to various losses such as leaching, fixation, denitrification, and volatilization, particularly at higher levels of application[64]. This decline is evident in the reduced use efficiency observed under higher phosphorus levels, likely because the increase in yield was less than the supply from both soil and fertilizer. Similar results have been documented in previous studies[65,66], where high phosphorus application rates led to decreased agronomic use efficiency due to greater losses. Combining higher phosphorus doses with nano DAP foliar sprays improved phosphorus uptake and use efficiency by ensuring timely nutrient supply and effective nitrogen partitioning to the spike and grain. These findings align with those of Attri et al.[67] and Bhat et al.[68], who suggested that synchronizing crop nitrogen demand with fertilizer nitrogen supply using nano DAP can enhance both crop recovery and nutrient use efficiency. Moreover, the use of low rates of foliar-sprayed nano-P may help to address mid-season phosphorus deficits in winter wheat, resulting in greater phosphorus use efficiency compared to traditional soil applications[18]. Treatments with minimal or no fertilizer application reduced the cost of cultivation compared to those with higher fertilizer doses, primarily due to the increased cost of fertilizers and the expenses associated with their application at higher levels. In our study, the treatment involving 100% RDP + two nano DAP sprays recorded the highest cost of cultivation, which can be attributed to the higher cost of nano DAP compared to conventional DAP fertilizers, the increased number of sprays required, and the associated application costs[69]. Despite these higher costs, this treatment also yielded the highest gross and net returns, driven by the increased grain and straw yields. The gross returns reflect the enhanced yields achieved with these treatments. Applying 75% RDP with nano DAP foliar sprays is also recommended for its economic benefits, as the returns were comparable to or slightly higher than returns from 100% RDP (conventional P application).

Conclusion

This research holds significant implications for farmers grappling with the challenges that can be addressed by the use of nano DAP foliar sprays for sustainable agricultural practices. Optimizing phosphorus application by reducing 25% RDP, and with 75% RDP + nano DAP foliar sprays at 5 ml L^{-1} at 20–25 DAS and 40–45 DAS can significantly enhance the yield, improve the nutrient use efficiency, and economic returns of wheat crop. This could be a novel nutrient-savvy concept in improving the growth and productivity of wheat, as it saved 25% recommendation dose P if supplied as nano DAP and can be a suitable substitute for P, as it possibly reduces P application and obtains similar yields to 100% RDP. Our experimental study offers a beacon of hope and a tangible pathway toward resilient and economically viable farming practices. However, despite the promising potential of nanotechnology in agriculture, there is still a need for comprehensive studies to assess the relative efficacy of nano-DAP in wheat cultivation.

Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to private and ethical restrictions.

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Y.S.S., D.K., led the research work, planned, supervised, and conducted field experiments, and read and edited the manuscript. K.S.R., R.B.B., K.D., S.M., S.N., K.B., G.A., collected soil/plant samples and performed chemical & statistical analysis, also wrote the initial draft of the manuscript, and prepared figures, and tables. Y.S.S., D.K., B.K.P., R.B., project supervision, reviewed, read, and edited the manuscript with significant contributions.

Declarations

Competing interests
The authors declare no competing interests.

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