



RESEARCH ARTICLE

Response of broccoli (*Brassica oleracea* L. var. *italica*) to foliar application of nano di-ammonium phosphate (DAP)

Pritiparna Jena*, Subhashree Panda, Alok Nandi & Nirmalya Dhal

Department of Vegetable Science, Institute of Agricultural Sciences, Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar 751 029, Odisha, India

*Correspondence email - pritiparnajena2002@gmail.com

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Abstract

Broccoli (*Brassica oleracea* L. var. *italica*) is a nutrient rich cruciferous vegetable valued for its vitamins, antioxidants and minerals. Using nano di-ammonium phosphate (DAP) in vegetable production has become important due to improve nutrient use efficiency, control nutrient release and reduce nutrient losses and leads to increased crop productivity and sustainability. A field experiment was conducted during the rabi season of 2024 to evaluate the effects of two nano DAP formulations (8 : 16 : 0 and 2 : 5 : 0) as foliar sprays at different concentrations in combination with 75 % of recommended dose of nitrogen and phosphorus (RDNP) on broccoli hybrid NS 50. The trial used randomised block design (RBD) with 10 treatments and 3 replications. The results revealed that the treatment with 75 % RDNP + nano DAP (2 : 5 : 0) at 5 mL L⁻¹ recorded the highest root girth (23.14 cm), north-south plant spread (67.13 cm), main head weight (440.17 g), head diameter (15.23 cm), marketable yield (12681.40 kg ha⁻¹), number of side sprouts (6.00) and ascorbic acid content (95.08 mg/100 g), achieving a 23.76 % higher yield than 100 % recommended dose of fertiliser (RDF). The above-mentioned treatment also ensured the earliest head initiation (67 days after sowing (DAS)), 50 % head initiation (68 DAS) and peak harvest (84 DAS) along with the highest soil organic carbon (SOC) (10.31 g kg⁻¹), net income (₹936781) and benefit-cost ratio (2.60). This study suggests that 75 % RDNP + nano DAP (2 : 5 : 0) at 5 mL L⁻¹ is highly effective for improving growth, earliness, yield, quality, economic returns and soil fertility of broccoli, while lowering the requirement of conventional fertilisers up to 25 %.

Keywords: broccoli; economic returns; nano fertilisers; soil fertility; yield

Introduction

Nanotechnology uses materials sized 1–100 nm and has become an important tool in modern science. In agriculture, it is applied as nano fertilisers, pesticides and herbicides to enhance crop production. Nano fertilisers are conventional nutrients encapsulated within nanomaterials that enable controlled nutrient release in soil (1). This innovation ensures sustained nutrient availability, improves crop yield and reduces nutrient losses (2). Their high solubility, large surface area and targeted nutrient delivery make them effective and environmentally friendly (3). Nano di-ammonium phosphate (DAP) is an advanced nano fertiliser that supplies nitrogen (N) and phosphorus (P) in nano form. Because of their smaller particle size, nano DAP particles can more easily penetrate plant tissues, leading to enhanced nutrient uptake, increased root growth and improved crop productivity (4). Nano DAP presents numerous agronomic and ecological benefits. It boosts nutrient use efficiency, which consequently decreases the amount of fertiliser needed to achieve optimal crop yields. This technology also reduces nutrient loss caused by leaching and volatilisation, helping to lower environmental pollution and enhance soil nutrient retention (5). Research indicates that nano DAP boosts crop yield and quality by enhancing the utilisation of P and N, fostering improved root growth and increasing plant resilience in stressful conditions (6). Additionally, the application of nano DAP contributes to sustainable

farming practices by reducing reliance on excessive chemical fertilisers and finite phosphate resources (7). Indian Farmers Fertiliser Cooperative Limited (IFFCO) introduced nano DAP in 2023; it contains 8 % N and 16 % P in liquid form. Studies involving cereals, vegetables and fruit crops have shown notable enhancements in yield, nutrient absorption and resistance to both biotic and abiotic stresses after the use of nano DAP (8).

Broccoli (*Brassica oleracea* L. var. *italica*) is a highly nutritious cole crop that belongs to the family Brassicaceae and valued for its edible flower heads and tender stems (9). It grows best at temperatures between 15 and 25 °C in fertile well drained loamy to sandy loam soil with pH around 6.0–7.0, adequate organic matter and moisture to aid in quality head formation. Broccoli heads are rich in vitamins A, B₁, B₂ and C, proteins, carbohydrates and mineral elements like calcium (Ca), P, potassium (K) and iron (Fe) (10, 11). It is also good for eye health as it contains antioxidant named zeaxanthin (12). One hundred grams of edible broccoli contain approximately 2500 IU vitamin A, 113 mg vitamin C, 3.6 g protein, 5.9 g carbohydrates, 103 mg Ca, 78 mg P and 382 mg K (11). Phytochemicals like glucosinolates, sulforaphane and 3,3'-diindolylmethane are also found in broccoli. These bioactive compounds have antioxidant, antiviral, antibacterial and anticarcinogenic effects that help in improving the immune system, maintaining good liver health and lowering the risks of stomach,

breast and colorectal cancer (13–15). The distinctive taste and aroma of broccoli are due to glucosinolate compounds, which are activated by the enzyme myrosinase when preparing and consuming the vegetable.

According to Food and Agriculture Organization (FAO), cultivation and demand of broccoli are increasing around the world, due in part to health trends and opportunities for export (16). Based on 2020 statistics from FAO, the global area of cultivation for broccoli and cauliflower was around 1.468 M ha, producing 17.457 Mt of crop output. China remains the leading producer, contributing approximately 10–12 Mt per year, which accounts for nearly 50 % of the global output (17). India follows as the second-largest producer, with an annual production of more than 9 Mt. In India, it is being increasingly adopted in states like Himachal Pradesh, Uttarakhand, Maharashtra, Karnataka and Tamil Nadu. However, there has been little research in India, particularly in Odisha, to assess impact of nano DAP fertilisers on broccoli farming. Therefore, this study aims to investigate the effects of nano DAP on the growth, yield, quality and economics of broccoli production.

Materials and Methods

The field experiment was conducted during November 2024 to February 2025 at Agriculture Research Station, Chhatabara, Faculty of Agricultural Sciences, Sikhsha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. The site lies 25.5 m above mean sea level at 20°23' N latitude and 85°83' E longitude, about 73 km from the Bay of Bengal, in the Eastern Coastal Plain Agroecological Region of the East and South East Coastal Plains. The climate is marked by hot, humid summers and mild winters. During the cropping season from November 2024 to February 2025, average temperatures ranged from 12–35 °C with relative humidity 60–66 %. Rainfall was maximum in December (100 mm), with no rain in January. The sunshine hours ranged from 8–8.6 hr and the wind speed varied from 6.6–8.5 km hr⁻¹. Initial soil study revealed that the soil was moderately acidic, non-saline (pH 6.33; EC 0.12 dS m⁻¹), with medium organic carbon (C) (9.97 g kg⁻¹), low P (23.3 kg ha⁻¹) and high K (121.0 kg ha⁻¹).

Details of cultural operations

The field experiment was conducted during the rabi season of 2024–25 at the Agriculture Research Station. The experiment was laid out in randomised block design (RBD) with 10 treatments and 3 replications. The study focused on two nano DAP formulations: IFFCO nano DAP (8 % N and 16 % P₂O₅) and Gromor nano DAP (2 % N and 5 % P₂O₅). Indian Farmers Fertiliser Cooperative Limited (IFFCO) nano DAP provides an effective source of N and P to provide nutrient needs in crops. Gromor nano DAP is a liquid fertiliser with nanoparticles of DAP.

Seeds of broccoli hybrid NS 50 were first treated with captan at 2 g kg⁻¹ of seeds and were sown on the nursery bed on November 6, 2024. For main field preparation, three ploughings were done, followed by laddering and leveling to achieve a fine tilth and uniform surface. Farmyard manure (FYM) at 10 t ha⁻¹ was added at the time of land preparation to improve soil fertility and structure. A combination of urea and single super phosphate at 75 or 100 % of the recommended dose, while MOP was applied as basal uniformly at 100 % of recommended dose of fertiliser (RDF) during the final land preparation. At 30 days after sowing (DAS), the first top dressing was done along with the first foliar spray of IFFCO nano

DAP and Gromor nano DAP. The second top dressing, along with the second foliar spray of the same nano fertilisers, was performed 45 DAS to support the later stages of plant growth and development.

Twenty-four days old seedlings were transplanted in the net area measuring 243 m² with 60 cm row to row spacing and 45 cm plant to plant spacing. Gap filling was done at 10 days after transplanting (DAT) to ensure a uniform stand of 30 plants per subplot. Intercultural activities included hoeing, manual weeding and earthing-up at 30 DAT, along with irrigation every 2–3 days based on soil moisture. Furrow irrigation was done immediately after top dressings to support nutrient uptake. For pest management against diamondback moth and thrips, the first spraying of fipronil 5 % suspension concentrate (SC) at 2 mL L⁻¹ of water was done around 10 DAT and the second spray was applied about 40 DAT. To control bacterial diseases, a spray of bactericide mixture containing plantomycin at 0.5 g and saaf at 3 g L⁻¹ of water was applied about 40 DAT.

Treatment details

T₁ = 100 % RDF (No nano fertiliser spray)

T₂ = 75 % RDNP

T₃ = T₂ + Nano DAP (8 : 16 : 0) foliar spray at 2 mL L⁻¹

T₄ = T₂ + Nano DAP (8 : 16 : 0) foliar spray at 3 mL L⁻¹

T₅ = T₂ + Nano DAP (8 : 16 : 0) foliar spray at 4 mL L⁻¹

T₆ = T₂ + Nano DAP (8 : 16 : 0) foliar spray at 5 mL L⁻¹

T₇ = T₂ + Nano DAP (2 : 5 : 0) foliar spray at 2 mL L⁻¹

T₈ = T₂ + Nano DAP (2 : 5 : 0) foliar spray at 3 mL L⁻¹

T₉ = T₂ + Nano DAP (2 : 5 : 0) foliar spray at 4 mL L⁻¹

T₁₀ = T₂ + Nano DAP (2 : 5 : 0) foliar spray at 5 mL L⁻¹

RDF = N : P₂O₅ : K₂O, 150 : 60 : 60 kg ha⁻¹

FYM = 10 t ha⁻¹

100 % K was applied in all treatments

Sampling technique

To avoid any error and bias in data collection, five plants were randomly selected from each subplot, excluding those along the borders to eliminate edge effects. The five randomly selected plants were tagged and used as sample subjects for assessing various growth, yield and quality parameters throughout the experimental season. The parameters measured from each subplot were plant height (cm), leaves per plant, leaf area (sq.cm), leaf length (cm), leaf width (cm), plant spread, root length (cm), root girth (cm), days to head initiation, days to 50 % head initiation, days to 1st harvest, days to peak harvest, main head diameter (cm), fresh weight of main head (kg), main head yield (kg ha⁻¹), number of side sprouts per plant, soil plant analysis development (SPAD) value, total soluble solids (TSS) (°Brix), glucose (%), sucrose (%) and ascorbic acid (mg/100 g) (18, 19).

Economic analysis

Gross return was derived by multiplying the head yield (kg ha⁻¹) obtained under each treatment by the prevailing sale price of head that is ₹60 per head at the time of harvest. This calculation provided the total income generated per hectare for each treatment, offering a direct reflection of the monetary value of the produce without accounting for production costs. Net return was calculated by

deducting the cost of cultivation for each treatment from its corresponding gross return. This value indicated the actual profit or gain obtained from each treatment after covering all input and operational expenses. It served as an essential parameter to assess the economic viability of the different treatments.

Benefit : cost ratio

The benefit : cost (B : C) ratio was calculated by dividing the gross return by the total cost of cultivation incurred for each treatment. This ratio provided an estimate of the economic efficiency of the treatments, where a higher B : C ratio indicated better profitability. It is a useful index for comparing the return on investment across all treatments.

Statistical analysis

The collected data on growth, yield and quality traits were statistically examined through analysis of variance (ANOVA). The experiment was laid out in a RBD to minimise the effects of field variability and enhance accuracy. Standard error of mean (S Em $\pm$) and critical difference (CD) at a 5 % probability level were computed for each parameter to assess the significance of variation among treatment means. These statistical measures ensured precise and reliable interpretation of the experimental findings.

Results and Discussion

Observations on vegetative parameters, phenological phases, yield and yield attributes were recorded in a systematic manner and the results are presented below.

Vegetative growth

Plant height (cm)

The data in Table 1 shows clear differences in plant height across the treatments used. Treatment T₁, which involved 100 % of the (RDF, achieved the highest plant height of 47.28 cm. In contrast, treatment T₅, which used 75 % of RDNP with a nano DAP foliar spray at 4 mL L⁻¹, resulted in the shortest plant height of 41.28 cm. All the treatments were statistically similar in their effect on plant height.

Leaves per plant

According to Table 1, the highest number of leaves (18.00) was observed in both T₄ (75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L⁻¹) and T₆ (75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L⁻¹). The lowest number of leaves (11.00) was recorded in T₉ (75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L⁻¹). All treatments were statistically at par in terms of their effect on the number of leaves per plant.

Leaf length (cm)

In the case of leaf length T₁₀ (75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L⁻¹) showed the lowest leaf length of 22.22 cm. The treatment T₄ (75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L⁻¹) recorded the highest leaf length of 24.30 cm among all 10 treatments (T₁–T₁₀), demonstrating a relatively better performance in terms of vegetative growth; however, none of the 10 treatments had significantly superior or inferior influence on leaf length and all 10 treatments were statistically at par.

Leaf width (cm)

The treatment T₃ (75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L⁻¹) showed the largest leaf width, suggesting superior vegetative growth, while T₆ (75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L⁻¹) recorded the lowest leaf width, indicating relatively less favourable performance in terms of leaf expansion (Table 1). All the treatments were statistically at par with each other resulting in no significance difference among treatments.

Leaf area (sq.cm)

According to Table 1, the treatment T₅ recorded the highest leaf area of 443.09 cm², followed closely by T₃ with 428.49 and T₁ with 408.41 cm², while the lowest leaf area was observed in treatment T₈ (75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L⁻¹), with a value of 347.79 cm². After comparing the treatment means, it was found that T₅ was statistically at par with treatments T₁, T₂, T₃, T₄, T₆, T₇ and T₉ but significantly superior to treatment T₈. Hence, it can be interpreted that T₅ performed the best in terms of leaf area, while T₈ exhibited the least performance. Findings from the present study are well supported by earlier research (20–24).

Table 1. Effect of nano di-ammonium phosphate (DAP) fertiliser on vegetative growth parameters of broccoli

Treatments	Plant height (cm)	Leaves/ plant	Leaf length (cm)	Leaf width (cm)	Leaf area (sq.cm)	Root length (cm)	Root girth (cm)	N-S plant spread (cm)	E-W plant spread (cm)
T ₁ 100 % RDF (No nano fertiliser spray)	47.28	17.33	24.15	18.92	408.41	15.28	20.31	61.36	59.55
T ₂ 75 % RDNP	43.75	16.67	23.82	18.44	401.05	18.74	19.97	52.24	54.75
T ₃ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L ⁻¹	45.77	17.67	24.12	19.53	428.49	18.02	20.50	62.70	58.63
T ₄ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L ⁻¹	42.71	18.00	24.30	18.32	388.87	21.05	21.80	56.48	54.31
T ₅ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L ⁻¹	42.28	16.33	23.91	18.31	443.09	18.27	21.04	48.18	54.09
T ₆ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L ⁻¹	44.85	18.00	23.40	17.17	354.09	18.53	21.27	56.77	57.07
T ₇ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L ⁻¹	45.24	17.00	23.59	17.91	362.94	22.33	19.83	57.36	57.77
T ₈ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L ⁻¹	43.17	17.33	22.99	17.65	347.79	17.76	21.50	55.53	53.77
T ₉ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L ⁻¹	45.44	11.00	22.97	17.82	352.65	17.82	22.43	55.52	51.51
T ₁₀ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L ⁻¹	45.51	12.33	22.22	17.87	366.21	18.93	23.14	67.13	57.19
SE (m) $\pm$	2.55	2.52	0.88	0.78	31.98	0.81	1.02	0.98	2.59
CD (0.05)	7.57	7.48	2.62	2.33	95.01	2.42	3.02	2.41	6.34

DAP: di-ammonium phosphate; RDNP: recommended dose of nitrogen and phosphorus; RDF: recommended dose of fertiliser.

Root length (cm)

The treatment T₇ (75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L⁻¹) demonstrated the longest root of 22.33 cm, resulting in its superior performance to all treatments (Table 1). The following revealed comparatively greater root lengths: T₄ (21.05 cm), T₁₀ (18.93 cm), T₂ (18.74 cm), T₆ (18.53 cm), T₅ (18.27 cm) and T₃ (18.02 cm). The treatments T₇ and T₄ were statistically at par however, significantly superior to T₁, T₂, T₃, T₅, T₆, T₈, T₉ and T₁₀. Moreover, the treatments T₂, T₃, T₅, T₆, T₈, T₉ and T₁₀ remained statistically similar to each other in the expression of root length (25).

Root girth (cm)

The analysis revealed significant differences among the treatments for root girth (Table 1). The treatment T₁₀ recorded the highest mean root girth (23.14 cm) and was found to be significantly superior to others, while T₇ recorded the lowest value (19.83 cm). Treatment T₁₀ was statistically different from treatments T₂ and T₇ however, statistically at par with T₁, T₃, T₄, T₅, T₆, T₈ and T₉.

North-south plant spread (cm)

The treatment T₁₀ recorded the highest N-S plant spread of 67.13 cm and was significantly superior to all other treatments. T₃ (62.70 cm) and T₁ (61.36 cm) were statistically at par with each other but significantly lower than T₁₀. T₄ (56.48 cm), T₆ (56.77 cm), T₇ (57.36 cm), T₈ (55.53 cm) and T₉ (55.52 cm) formed a statistically similar group and were at par among themselves but significantly lower than T₁, T₃ and T₁₀. T₂ with a plant spread of 52.24 cm was significantly lower than the higher group of treatments, but superior to T₅, which recorded the lowest mean of 48.18 cm and was significantly different and inferior to all other treatments. The foliar application of nano DAP enhanced the immediate uptake of N and P, leading to increased photosynthetic activity, rapid cell division and elongation, better leaf expansion and ultimately greater N-S plant spread (21).

East-West plant spread (cm)

The treatment T₁ recorded the highest E-W plant spread (59.55) which is statistically at par with T₂ (54.75 cm), T₃ (58.63 cm), T₄ (54.31 cm), T₅ (54.09 cm), T₆ (57.07 cm), T₇ (57.71 cm), T₈ (53.77 cm) and T₁₀ (57.19 cm) but statistically superior to T₉ (51.51 cm). Therefore, it can be concluded that T₉ recorded the lowest E-W plant spread and was statistically inferior to the top performing

group. Foliar spray of nano DAP may have stimulated efficient uptake of essential nutrients, thereby increasing photosynthetic activity and E-W plant spread in broccoli (21).

Phenological characters

Days to head initiation (DAS)

The treatment T₁₀ (75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L⁻¹) recorded the least number of days that is 67.00 DAS to head initiation, indicating earliest head initiation while T₅ (75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L⁻¹) took more number of days that is 71.33 DAS (Table 2). Statistically, T₅ was significantly different from T₂, T₃, T₇, T₈, T₉ and T₁₀. Treatments T₁ (70.00 DAS) and T₄ (69.67 DAS) were statistically at par with T₅. On the other hand, treatments T₂, T₃, T₆, T₇, T₈, T₉ and T₁₀ were statistically at par with each other, showing no significant differences in their time to head initiation. Early head initiation occurred due to foliar spray of nano DAP, as its smaller particle size helps in quick absorption of N and P, leading to faster plant growth (26).

Days to 50 % head initiation (DAS)

The treatment T₁₀ (75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L⁻¹) recorded the least number of days that is, 68.00 DAS to 50 % head initiation, which was statistically at par with T₁, T₃ and T₉ (Table 2). On the other hand, T₂ (75 % RDNP) took the highest time that is, 72.67 DAS which was significantly different from T₉ and T₁₀ but statistically at par with rest of the treatments. Treatment T₁, T₃, T₄, T₅, T₆, T₇, T₈ and T₉ were statistically at par with each other, indicating no significant differences in their time of 50 % head initiation. It may have occurred due to better nutrient absorption and higher photosynthetic activity, which helped the plants grow faster and initiate heads earlier.

Days to first harvest (DAS)

Among the treatments, T₆ recorded the minimum number of days that is, 81.33 DAS to first harvest, indicating the earliest maturity. On the other hand, T₅ and T₈ recorded the maximum number of days, that is, 84 DAS to first harvest, suggesting delayed maturity (Table 2). But all the treatments were at par with each other, which means there are no significant differences between the treatments. The variation in days to first harvest may be associated with higher N availability, which encouraged vegetative growth and delayed maturity.

Table 2. Effect of di-ammonium phosphate (DAP) fertilisers on phenological characters of broccoli

Treatments	Days to head initiation (DAS)	Days to 50 % head initiation (DAS)	Days to 1 st harvest (DAS)	Days to peak harvest (DAS)
T ₁ 100 % RDF (No nano fertiliser spray)	68.00	70.33	82.33	86.67
T ₂ 75 % RDNP	66.00	72.67	83.33	86.67
T ₃ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L ⁻¹	66.33	70.33	82.33	84.00
T ₄ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L ⁻¹	67.67	71.33	84.00	85.33
T ₅ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L ⁻¹	69.33	71.33	84.00	85.33
T ₆ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L ⁻¹	66.67	70.67	81.33	85.33
T ₇ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L ⁻¹	65.67	71.33	83.33	85.33
T ₈ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L ⁻¹	66.00	71.00	84.00	85.33
T ₉ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L ⁻¹	65.67	70.00	82.33	85.33
T ₁₀ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L ⁻¹	66.00	68.00	81.67	84.00
SE (m) ±	0.67	0.83	0.95	1.57
CD (0.05)	2.26	2.45	2.84	4.65

DAP: di-ammonium phosphate; DAS: days after sowing; RDNP: recommended dose of nitrogen and phosphorus; RDF: recommended dose of fertiliser.

Days to peak harvest (DAS)

The shortest duration to reach peak harvest was noted with treatments T₃ and T₁₀, as both took 84.00 DAS, indicating their early maturity. The longest time to reach peak harvest was observed in T₁ and T₂ with 86.67 DAS (Table 2). However, all the treatments remained statistically at par with each other.

Yield and yield attributing characters

Main head weight (g)

The highest fresh weight of the main head was noted with treatment T₁₀ (440.17 g), which was significantly superior to all other treatments (Table 3). It was followed by T₉ (473.17 g) and T₈ (332.24 g), which were statistically at par with each other but significantly superior to the remaining treatments. Nano DAP fertiliser enhances nutrient absorption and improves nutrient-use efficiency because of their small particle size. This results in reduced nutrient loss and promotes better crop growth. Sufficient N levels boost photosynthesis, support cell division and promote leaf expansion, which collectively increase photosynthetic activity and ultimately lead to higher yields (20, 26).

Main head diameter (cm)

The treatment T₁₀ (15.23 cm) had the highest main head diameter, which was statistically at par with T₃, T₄ and T₉ but significantly higher than T₁, T₂, T₅, T₆ and T₇ (Table 3). Similarly, T₃ (14.10 cm) and T₉ (14.03 cm) were also statistically at par with T₁, T₂, T₅ and T₇ but significantly superior to T₆. The treatments T₁, T₂, T₅, T₆ and T₇ were found statistically at par with each other and did not show any significant differences in head diameter. This analysis highlights that T₁₀ performed best in terms of main head diameter, closely followed by T₄, while T₆ showed the lowest value. The differences in main head diameter observed across various treatments might be due variations in nutrient availability and uptake. These differences likely influenced photosynthetic activity, cell division and the accumulation of photosynthates, ultimately affecting head development and enlargement.

Yield (kg ha⁻¹)

The treatment, T₁₀ produced the highest yield (12681.40 kg ha⁻¹) and was statistically superior to T₁ (10246.31 kg ha⁻¹), T₂ (9020.54 kg ha⁻¹), T₃ (10090.01 kg ha⁻¹), T₄ (9748.60 kg ha⁻¹), T₅ (10349.15 kg ha⁻¹) and remained statistically at par with T₆ (10583.61 kg ha⁻¹), T₇ (10908.56 kg ha⁻¹) and T₈ (10752.25 kg ha⁻¹) and T₉ (11560.93 kg ha⁻¹). The treatment T₉ produced significantly higher yield than T₂; however, it was statistically at par with T₁₀ and other treatments. Treatments T₁, T₃, T₄, T₅, T₆, T₇ and T₈ were statistically at par with each other. In the study the treatments, T₉ and T₁₀ emerged as the

highest-yielding, while the others showed comparable performance without significant differences. The differences in yield among treatments may be linked to variations in nutrient absorption and utilisation, which influenced plant growth, photosynthetic activity and head development. Enhanced growth and greater accumulation of photosynthates ultimately led to higher yield (24, 26–32).

Number of side sprouts

The treatment T₁₀ produced the highest number of side sprouts (6.00) and was statistically superior to T₁ (4.00), T₂ (3.67), T₅ (4.60) and T₆ (4.20). T₉ (5.80), T₈ (5.53) and T₇ (5.47) also exhibited higher values and were statistically at par with T₁₀. The lowest number of side sprouts was recorded in T₂ (3.67), which was statistically inferior to all the treatments except T₁ and T₆.

Biochemical parameters

According to Table 4, the highest SPAD value indicating chlorophyll content was recorded in T₈ (71.50) and the lowest chlorophyll content was observed in T₁ (67.37), though they were not significant. The highest TSS was recorded in T₂ (6.59 °Brix), which was statistically superior to T₁, T₃, T₄, T₅, T₈, T₉ and T₁₀ but statistically at par with T₆ and T₇. The results revealed that T₂ and T₆ were the most effective treatments for improving TSS content, followed by T₇, T₃, T₁₀ and T₈, while T₅ recorded the lowest TSS level among all treatments. Similar findings were reported by previous researchers, who observed that the application of 75 % RDNP combined with two foliar sprays of nano DAP at 0.7 % significantly increased the TSS content in tomato (33). This enhancement in TSS may be due to the presence of growth-promoting substances that facilitated the synthesis and accumulation of carbohydrates, vitamins and other quality components within the fruits. The highest sucrose content was observed with T₂ (6.62 g/100 g), which was found to be statistically at par with T₆ (6.21 g/100 g) and T₇ (6.07 g/100 g), indicating no significant differences among them but superior to T₁, T₃, T₄, T₅, T₈, T₉ and T₁₀. The treatments T₂, T₆ and T₇ are more effective in enhancing sucrose content compared to the rest. The highest glucose content was recorded with T₂ (6.66 g/100 g), which was statistically at par with T₆ (6.32 g/100 g) and T₇ (6.00 g/100 g) but significantly superior to T₁, T₃, T₄, T₅, T₈, T₉ and T₁₀. The highest ascorbic acid was recorded in T₁₀ (95.08), which was significantly superior to T₁, T₂, T₃, T₄, T₅, T₇, T₈ and T₉, but at par with T₆. The increase in ascorbic acid content may be due to enhanced nutrient use efficiency and enzymatic activities induced by nano DAP, which improved photosynthetic rate and carbohydrate accumulation, thereby promoting the biosynthesis of ascorbic acid (20, 33).

Table 3. Effect of di-ammonium phosphate (DAP) fertilisers on yield and yield attributing characters of broccoli

Treatments	Main head weight (g)	Main head diameter (cm)	No. of side sprouts	Yield (kg ha ⁻¹)	Extra yield over T ₁ (%)
T ₁ 100 % RDF (No nano fertiliser spray)	311.21	12.67	4.00	10246.31	-
T ₂ 75 % RDNP	297.07	12.62	3.67	9020.54	-
T ₃ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L ⁻¹	323.51	14.10	5.07	10090.01	-
T ₄ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L ⁻¹	323.05	15.14	4.93	9748.60	-
T ₅ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L ⁻¹	316.27	12.57	4.60	10349.15	1.00
T ₆ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L ⁻¹	314.95	12.31	4.20	10583.61	3.29
T ₇ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L ⁻¹	328.15	12.82	5.47	10908.56	6.47
T ₈ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L ⁻¹	332.24	13.40	5.53	10752.25	4.93
T ₉ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L ⁻¹	373.61	14.03	5.80	11560.93	12.83
T ₁₀ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L ⁻¹	440.17	15.23	6.00	12681.40	23.76
SE (m) ±	14.65	0.64	0.21	719.78	-
CD (0.05)	43.53	1.89	0.65	2138.34	-

DAP: di-ammonium phosphate; RDNP: recommended dose of nitrogen and phosphorus; RDF: recommended dose of fertiliser.

Table 4. Effect of di-ammonium phosphate (DAP) fertilisers on biochemical parameters of broccoli

Treatments	SPAD value	TSS (°Brix)	Sucrose (g/100g)	Glucose (g/100g)	Ascorbic acid (mg/100 g)
T ₁ 100 % RDF (No nano fertiliser spray)	67.37	4.96	5.07	5.11	81.50
T ₂ 75 % RDNP	67.47	6.59	6.62	6.66	79.54
T ₃ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L ⁻¹	68.93	5.47	5.63	5.57	81.57
T ₄ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L ⁻¹	69.97	4.98	5.27	5.27	84.21
T ₅ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L ⁻¹	69.97	4.38	4.49	4.50	84.54
T ₆ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L ⁻¹	69.20	5.99	6.21	6.32	92.54
T ₇ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L ⁻¹	70.13	5.93	6.07	6.00	82.45
T ₈ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L ⁻¹	71.50	5.36	5.26	5.42	84.48
T ₉ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L ⁻¹	69.73	4.91	4.85	4.89	85.08
T ₁₀ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L ⁻¹	70.50	5.37	5.44	5.37	95.20
SE (m) ±	2.04	0.35	0.32	0.33	1.02
CD (0.05)	6.05	1.04	0.95	0.98	3.02

DAP: di-ammonium phosphate; RDNP: recommended dose of nitrogen and phosphorus; RDF: recommended dose of fertiliser; SPAD: soil plant analysis development; TSS: total soluble solids.

Soil parameters

pH

The initial soil pH prior to treatment application was 6.33. An overview of final soil sample data in Table 5 indicated that the highest pH value (7.24) was reported in T₆ and the lowest pH (6.30) was recorded in T₅ as final soil sample data. The increase in soil pH might be due to the release and accumulation of cations in the soil solution, which helped neutralise soil acidity. The slight reduction in soil pH in treatment T₅ could be due to continuous absorption of nutrients by plants and release of organic acids in the rhizosphere during crop growth.

Electrical conductivity (dS m⁻¹)

The maximum EC value (0.52 dS m⁻¹) was recorded in T₉ and the minimum EC (0.30 dS m⁻¹) was recorded in T₁₀ (Table 5). The soil electrical conductivity (EC) increased in all treatments compared to the initial EC value of 0.12 dS m⁻¹. The increase in soil EC might be due to higher availability of soluble salts at increased soil pH and release of more nutrient ions through decomposition of organic matter in the soil.

Organic carbon (g kg⁻¹)

A perusal of Table 5 reveals that the highest soil organic carbon (SOC) (10.31 g kg⁻¹) was recorded in T₁₀ and the lowest SOC was recorded in T₂ (5.33 g kg⁻¹). Increase in organic C might be due to higher microbial activity and better plant growth.

Available phosphorus (kg ha⁻¹)

The highest available P was seen in the treatment T₃, T₅ and T₇ (29.1 kg ha⁻¹) which was higher than T₂, T₄, T₆, T₈, T₉ and T₁₀ (Table 5). T₁ (24.4 kg ha⁻¹) has recorded the lowest soil P content.

Available potassium (kg ha⁻¹)

It is evident from Table 5 that the maximum soil K content was observed in treatment T₉ (462 kg ha⁻¹) and the minimum soil K content was observed in T₁ (321 kg ha⁻¹).

Economics

Table 6 shows that the treatment T₁₀ was best in terms of gross income (₹1521720), net income (₹936781) and B : C ratio (2.60). The minimum B : C ratio was observed in T₂ (1.87). The maximum and

Table 5. Analysis of final soil samples

Treatments	pH	Electrical conductivity (ds m ⁻¹)	Organic carbon (g kg ⁻¹ soil)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
T ₁ 100 % RDF (No nano fertiliser spray)	6.73	0.38	6.01	24.4	333.0
T ₂ 75 % RDNP	6.69	0.35	5.33	25.7	321.0
T ₃ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L ⁻¹	6.68	0.39	7.04	29.1	343.0
T ₄ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L ⁻¹	6.83	0.34	9.45	27.8	322.0
T ₅ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L ⁻¹	6.30	0.38	7.73	29.1	343.0
T ₆ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L ⁻¹	7.24	0.34	10.13	27.8	342.0
T ₇ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L ⁻¹	6.79	0.34	9.26	29.1	353.0
T ₈ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L ⁻¹	6.44	0.36	6.70	26.7	374.0
T ₉ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L ⁻¹	6.80	0.52	7.04	25.7	462.0
T ₁₀ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L ⁻¹	6.80	0.30	10.31	25.1	393.0

DAP: di-ammonium phosphate; RDNP: recommended dose of nitrogen and phosphorus; RDF: recommended dose of fertiliser.

Table 6. Economics of treatments

Treatments	Yield (kg ha ⁻¹)	Gross income (₹ ha ⁻¹)	Cost of cultivation (₹ ha ⁻¹)	Net income (₹ ha ⁻¹)	B : C ratio
T ₁ 100 % RDF (No nano fertiliser spray)	10246.31	1229520	577896	651623	2.12
T ₂ 75 % RDNP	9020.54	1082520	576188	506332	1.87
T ₃ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 2 mL L ⁻¹	10090.01	1210800	584984	625815	2.06
T ₄ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 3 mL L ⁻¹	9748.60	1169880	585882	583997	1.99
T ₅ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 4 mL L ⁻¹	10349.15	1241880	586780	655099	2.11
T ₆ 75 % of RDNP + nano DAP (8 : 16 : 0) foliar spray at 5 mL L ⁻¹	10583.61	1270080	587678	682401	2.16
T ₇ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 2 mL L ⁻¹	10908.56	1309080	583888	725191	2.24
T ₈ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 3 mL L ⁻¹	10752.25	1290240	584238	706001	2.20
T ₉ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 4 mL L ⁻¹	11560.93	1387320	584588	802731	2.37
T ₁₀ 75 % of RDNP + nano DAP (2 : 5 : 0) foliar spray at 5 mL L ⁻¹	12681.40	1521720	584938	936781	2.60

DAP: di-ammonium phosphate; RDNP: recommended dose of nitrogen and phosphorus; RDF: recommended dose of fertiliser.

minimum cost of cultivation was observed in T₆ (₹587678) and T₂ (₹576188) respectively. The superior performance of the treatment T₁₀ may be due to higher marketable yield and better-quality produce with comparatively lower cultivation cost (26, 31, 32, 34).

Conclusion

The results conclude that treatment T₁₀ (75 % recommended dose of nitrogen and phosphorus (RDNP) + nano di-ammonium phosphate (DAP) 2 : 5 : 0 at 5 mL L⁻¹ foliar spray) demonstrated the best overall performance in terms of growth, earliness, yield, yield attributes and economic returns. Further, the treatment resulted in the highest ascorbic acid content (95.08 mg/100 g), soil organic carbon (SOC) in the post-harvest soil (10.31 g kg⁻¹). It also increased the total yield by 23.76 % compared to 100 % recommended dose of fertiliser (RDF). In contrast, treatment T₉ (75 % RDNP + nano DAP 2 : 5 : 0 at 4 mL L⁻¹) proved most effective in improving soil health, recording the highest electrical conductivity (0.52 dS m⁻¹), pH (7.24) and available K (462 kg ha⁻¹). These results clearly indicate that nano DAP application not only enhances crop productivity and profitability but also improves soil fertility, contributing to sustainable agricultural production. According to this study, combination of 75 % RDNP with nano DAP 2 : 5 : 0 at 5 mL L⁻¹ as foliar spray is advisable for farmers to enhance yield, quality and economic benefits while decreasing reliance on traditional fertilisers. Further research may be carried out to evaluate the long term impact of nano DAP on soil health, nutrient availability and microbial activity in different agro climatic conditions. Research may also be done in order to determine the impact of nano DAP when combined with organic fertilisers and bio-fertilisers.

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Authors' contributions

All authors made substantial contributions to the study and the preparation of the manuscript. PJ and AN conceived and designed the study. PJ and SP conducted the field and laboratory experiments, collected and analysed the data, interpreted the results and prepared the initial draft of the manuscript. ND, PJ, SP and AN contributed to the literature review and critically revised the manuscript for intellectual content. All authors have read and approved the final version of the manuscript.

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During the preparation of this work the authors used Grammarly in order to avoid grammatical errors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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