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Physiological evaluation of nano DAP on growth and yield of tomato

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Abstract

Tomato (*Solanum lycopersicum*), a solanaceous crop, is widely cultivated worldwide. This study evaluates the impact of nano DAP (diammonium phosphate) on morpho-physiological traits, biochemical properties, yield and quality parameters. Eight treatments comprising varying proportions of DAP and nano DAP were evaluated for traits including plant height, leaf area, chlorophyll index, total dry matter production, gas exchange parameters, leaf soluble protein, total soluble solids (TSS), ascorbic acid, titratable acidity, firmness and fruit yield. The hybrid tomato variety 'Shivam' was cultivated in pot culture under a glasshouse at Tamil Nadu Agricultural University, Coimbatore, using a completely randomized design with five replications. Foliar sprays with different proportions of nano DAP and DAP were applied 30 and 45 days after transplanting. Among the treatments, 75% RDNP (recommended nitrogen and phosphorus dose) combined with two foliar sprays of nano DAP at 0.7% (T5) significantly increased plant height (48.90 cm and 54.31 cm), chlorophyll index (40.05 and 42.15), dry matter production (55.45 g plant^{-1}), TSS (5.52 °Brix), fruit production and ascorbic acid content. This treatment also improved gas exchange parameters, fruit firmness and overall `growth and productivity compared to other treatments. Conversely, the absolute control group demonstrated the lowest performance across all parameters. The study highlights that combining both conventional fertilizers with nano DAP considerably improves tomato growth by enhancing nutrient absorption, particularly nitrogen and phosphorus, which are essential for cell division, photosynthesis and energy transfer. Nano DAP, due to its small particle size and large surface area, effectively penetrates plant tissues, increasing nutrient availability, chlorophyll content and plant height. These findings underscore the potential of nano DAP to substantially enhance tomato yield and quality, thereby contributing to sustainable crop production.

Keywords

nano DAP; quality; *Solanum lycopersicum;* sustainable agriculture; yield

Introduction

Tomato (*Solanum lycopersicum*), a solanaceous crop, is widely cultivated in many regions. Originating in South America, it was introduced to Europe in the 16th century, where it quickly gained popularity as a key ingredient in salads and sauces. Tomatoes are self-pollinated and were introduced to India by the Portuguese. They are widely grown in home gardens, commercial fields, greenhouses and hydroponic systems (1). They are low in calories and rich in vitamins A and C, minerals, antioxidants such as lycopene and dietary fibers, which support heart health, help prevent cancer and enhance digestive wellness, making them a nutritious addition to a balanced diet (2).

Tomatoes also contain small amounts of B-complex vitamins, including thiamin, riboflavin and niacin and serve as a source of iron (3). Tomato plays a crucial role in the food processing industry, yielding products such as sauces, juices and canned goods. Food processing not only extends the shelf life of tomatoes but also reduces waste, which is vital for economic sustainability (4).

Globally, tomatoes rank as the second most important vegetable crop after potatoes, with an annual production of approximately 42.7 million metric tons (MT) of fresh weight (5). Tomato plants require essential nutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium and magnesium for optimal growth and development. Nutrient deficiencies can lead to significant crop loss, manifesting as stunted growth, leaf discoloration and reduced photosynthesis, which ultimately affect both the yield and quality (6). To meet the growing demand for tomatoes, it is critical to enhance crop production through appropriate agricultural techniques. Effective nutrient management strategies, such as the foliar application of key nutrients, can significantly improve production and productivity (7).

Diammonium phosphate (DAP) is the most widely used phosphatic fertilizer, valued for its favorable physical properties and high nutrient content, consisting of 18% nitrogen and 46% P_2O_5 (phosphorus pentoxide). As a source of both phosphorous (P) and nitrogen (N), DAP provides a balanced and essential nutrient combination that supports optimal plant growth, development and productivity. Highly soluble, it dissolves quickly in soil, releasing plant-available phosphate and ammonium ions (8). DAP plays a vital role in agriculture supporting plant growth, improving crop production and enhancing yields across a wide range of crops (9).

Despite its advantages, the application of DAP is associated with considerable nutrient losses, especially N. Addressing these losses is crucial for improving fertilizer efficiency and reducing environmental impacts (10). It is estimated that 30-50% of the N in DAP is not absorbed by crops, leading to substantial wastage and potential environmental consequences, including soil degradation, water pollution and increased greenhouse gas emissions (11). To mitigate these challenges, adopting sustainable agricultural practices, such as the use of nano fertilizers, has become increasingly important to mitigate fertilizer losses and nutrient deficiencies.

Nanotechnology is revolutionizing agriculture by enabling precision nutrient management and facilitating the targeted and controlled release of nutrients. This approach reduces nutrient waste, enhances crop yields and offers a sustainable solution for modern farming by optimizing resource use and minimizing environmental impact (12, 13). Nanotechnology integrates fundamental aspects of biological, physical and chemical sciences at the nanoscale. Physically, it involves reducing materials to nanometer dimension; chemically, it governs the formation of new bonds and influences chemical properties; and biologically, it facilitates actions at the nanoscale such as targeted drug delivery and bonding to specific sites (14).

Due to their tiny size, nanoparticles (NPs) possess an increased surface area, which enhances nutrient absorption, minimizing environmental impact and improving crop yields by efficiently delivering nutrients to plants. The use of DAP in nano form is particularly advantageous for improving yield potential and quality traits (15). Indian Farmers Fertiliser Cooperative Limited (IFFCO) nano DAP, a white liquid fertilizer contains 8.0% N (w/v) and 16.0% P (P_2O_5 w/v), with particle size less than 100 nm. When applied as a diluted foliar spray, nano DAP exhibits superior absorption capacity, effectively penetrating plant tissues through stomata, thus mitigating nutrient deficiencies and significantly increasing production and productivity (16).

Advances in nanotechnology have bolstered research on the foliar application of engineered nanoparticles. These NPs exhibit strong catalytic activity and can carry functional groups that enhance cellular uptake. For example, the efficacy of zinc oxide (ZnO) nano fertilizers on rice crops, achieving a 20-30% increase in grain yield compared to traditional zinc sulfate fertilizers. This improvement was attributed to enhanced zinc availability, which is crucial for root development, photosynthesis and overall crop growth, leading to increased biomass and grain yield (17). Similarly, a field study on maize crops treated with nano -nitrogen fertilizers produced 16-25% higher yields than those treated with conventional urea. The nano-nitrogen formulation enabled a slower release of nitrogen into the soil, reducing nutrient leaching and volatilization losses while ensuring a consistent nutrient supply throughout the crop growth stages and supporting enhanced production (18). Plants typically absorb foliar-applied nanoparticles through mechanisms such as stomata, cracks, water pores, ion channels, protein carriers, endocytosis, stigmas, wounds and trichomes (19). Compared to traditional soil-applied fertilizers, foliar-applied nano-fertilizers offer significant advantages, including faster nutrient absorption, improved cost-effectiveness and minimal impact on soil health. Additionally, foliar application supplies vitamins and essential elements that may be deficient in the soil (20). Consequently, ongoing research is focused on evaluating the impact of nano DAP on the growth and yield of tomato plants.

Materials and Methods

The seeds of tomato hybrid 'Shivam' were sown in portrays, with three seeds per cell. After 21 days, tomato seedlings were transplanted into pots filled with a mixture of red soil and sand in a 3:1 ratio, maintaining a pH of 7.2. The pot culture experiment was conducted in a glasshouse at the Department of Crop Physiology, Tamil Nadu Agriculture University, Coimbatore, during the period from January to May 2024. This experimental site is located in the Western agro-climatic zone of Tamil Nadu

The plants were manually watered according to their transpiration needs. Conventional fertilizers, including N (urea), P (SSP- single super phosphates) and K (MOP- muriate of potash), were applied as per the treatment specifications. Fertilizer application was conducted in three intervals at 30 and 50 days after transplanting (DAT). Potassium was uniformly applied across all treatments. Foliar sprays of nano DAP (0.7%) and DAP (2%) were performed at 30 DAT (during the flowering stage) and 50 DAT (during the fruit development) to assess the effect of nano DAP on the morpho-physiological traits, yield and quality of tomato plants.

Nano DAP was procured from IFFCO, while DAP was sourced from the Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore.

Treatment details

The experiment comprised eight treatments combining DAP and nano DAP in different proportions.

T1 : Recommended dose of fertilizer (RDF) + all package of practices

T2 : 50% RDNP

T3 : 50% RDNP + 2 sprays of nano DAP at 0.7% during flowering and fruit development

T4 : 75% RDNP

T5 : 75 % RDNP+ 2 sprays of nano DAP at 0.7% during flowering and fruit development

T6 : 75% recommended N through fertilizer +2 sprays of DAP at 2% during flowering and fruit development

T7 : 50% recommended N through fertilizer + 2 sprays of DAP at 2% during critical growth stages

T8 : Control (no nitrogen and phosphorus)

Observations were recorded following the first and second foliar spray for all treatments. The mean values were subjected to statistical analysis to ensure reliable and accurate interpretation of the results.

Morphological traits

Plant height (cm)

Plant height was measured from ground level to the tip of the tallest leaf using a scale. The results were recorded in centimetres (cm).

Leaf area (cm^2)

Leaf area was determined using a leaf area meter (LICOR, Model LI 3000). Leaf samples were collected from individual plants across all treatments and inserted into the meter to calculate the total leaf area per plant. The values were expressed in cm^2 per plant.

Total dry matter production (TDMP)

Plant samples were collected from each replication and treatment. These samples were air- dried in the shade for 2 days, followed by drying in a hot air oven at 80°C for 48 hours. The total dry matter production was expressed in g plant^{-1}.

Physiological trait

Chlorophyll index (SPAD value)

Chlorophyll index readings were obtained using a portable chlorophyll meter (Soil Plant Analytical Development, SPAD, Model 502). Third physiologically active leaf was chosen for measurement. Three readings, one from the top, one from the center and one from the bottom of the leaf, were taken for each replication. The average of these readings was then calculated (21).

Gas exchange parameters

The photosynthetic rate was measured using a portable photosynthesis system (LI-6400 XT, Licor Inc, Nebraska, USA) between 10:00 AM and 12:00 PM on clear, sunny day. Photosynthetically active radiation was maintained above 1000 µmol photons m^{-2} s^{-1}. The third leaf from the top, considered the physiologically active leaf, was placed in an IRGA (infrared gas analyzer) chamber to evaluate gas exchange properties (22). Prior to inserting the leaf, the photosynthetically active radiation was adjusted to exceed 1000 µmol photons m^{-1} s^{-1} and the CO_2 concentration within the chamber was aligned with ambient levels. The photosynthetic rate was expressed as µmol CO_2 (carbon dioxide) m^{-2} s^{-1}, stomatal conductance as mol H_2O m^{-2} s^{-1} and transpiration rate as mmol H_2O (water) m^{-2} s^{-1}.

Biochemical traits

Leaf-soluble protein (mg g^{-1})

The soluble protein content in the leaves was estimated (23). A 0.25 g leaf sample was macerated in 10 mL of phosphate buffer solution and centrifuged at 3000 rpm for 10 minutes. The supernatant was collected and diluted to 25 mL. From this, 1 mL was pipetted into a mixture of 5 mL ACT (alkaline copper tartrate) and 0.5 mL Folin reagent, allowing colour development for 30 minutes. The optical density was measured at 660 nm using a spectrophotometer and the results were expressed in mg g^{-1}.

Yield traits

Fruit yield (kg plant^{-1})

The average number of fruits produced per plant and their respective weights were recorded to calculate fruit yield per plant and results were expressed in kg plant^{-1}.

Number of flowers per plant

The total number of flower clusters per plant at each flowering stage, before pollination and fertilization, was determined by counting the cluster.

Number of fruits per plant

The total number of fruits produced per plant was recorded across all treatments and replications. The average was then calculated and expressed as the number of fruits per plants.

Fruit set percentage

The flower-to-fruit ratio represents the percentage of flowers that successfully develop into fruits compared to the total number of flowers produced.

Quality traits

Total soluble solid (TSS) (°Brix)

Total soluble solids (TSS) are key indicators of quality and ripeness in tomatoes, expressed as a percentage (°Brix). TSS was measured using an Erma hand refractometer (ERMA, RHB32ATC). Extracted tomato juice sample was placed on the refractometer prism and the Brix value was recorded.

Titratable acidity

The titratable acidity of tomato fruits was analyzed (24). About 2 g of tomato fruit was weighed and crushed in a glass mortar and the extracted juice volume was adjusted to 100 mL with distilled water in a volumetric flask. After filtering, 20 mL of the filtrate was placed in a conical flask, to which two drops of phenolphthalein were added. The solution was titrated with 0.1 N NaOH (sodium hydroxide) until a pink endpoint was observed, indicating the acidity. The results were calculated using a standard formula and expressed as a percentage of citric acid (24).

$$\text{Titratable acidity (\%)} = \frac{\text{Titratable value x Normality of NaOH X m.e.q.wt. of acid}}{\text{Volume of sample}} \times 100 \qquad \text{(Eqn. 1)}$$

External firmness

Fruit firmness was assessed using a penetrometer, which measures the resistance of the fruit's flesh using a standardized probe. A fruit hardness tester (LT Lutron, FR-5120, Taiwan) with a 5 mm stainless steel probe used to penetrated 10 mm into the sample. A trigger force of 10.01 N was applied and firmness was expressed in Newtons (N).

Ascorbic acid

The ascorbic acid content in tomato fruits was determined using a titration method (25). Initially, 10 mL of 4% oxalic acid was combined with 5 mL of a standard solution (0.1% ascorbic acid) and titrated with 2,6-dichlorophenol indophenol dye until a pink colour endpoint was observed. The volume of dye used was recorded as V1. Next, 500 mg of macerated tomato fruit was mixed with 4% oxalic acid and the total volume was adjusted to 100 mL with distilled water. After centrifuging at 3000 rpm for 15 minutes, 5 mL of the supernatant was combined with 10 mL of 4% oxalic acid and titrated against the dye. The volume of dye used was recorded as V2 when the pink endpoint appeared. The results were expressed as mg of ascorbic acid per 100 g of fruit.

$$\text{Amount of ascorbic acid in the sample} = \frac{0.5}{V1} \times \frac{V2}{5} \times \frac{100}{0.5} \times 100$$

(Eqn. 2)

Statistical analysis

The experiment was conducted using a completely randomized design with eight treatments and five replications to assess the effect of nano DAP on the morpho-physiological traits, yield and quality of tomato plants. Data were analyzed for significant differences using one-way analysis of variance (ANOVA) with SPSS 16.0 software. Statistical significance was determined at $p \leq 0.05$ by Ducan's multiple range test. The data was represented using GraphPad Prism 8 software.

Results

Effect of foliar spray of nano DAP on morpho-physiological traits of tomato

The foliar spray of nano DAP on tomato plants significantly enhanced their morpho-physiological traits. Significant differences were observed among treatments in plant height (cm), leaf area (cm^2), total dry matter production (g $plant^{-1}$) and chlorophyll index (SPAD) (Table 1). Among all treatments, the application of 75% RDNP combined with two sprays of nano DAP at 0.7% during flowering and fruit development (T5) significantly increased plant height, leaf area, total dry matter and chlorophyll index.

Plant height increased to 48.90 cm at flowering and 54.31 cm during fruit development. Leaf area expanded to 585.96 cm^2 and 987.05 cm^2, total dry matter production increased to 13.80 g $plant^{-1}$ and 37.85 g $plant^{-1}$ and SPAD values improved to 40.05 and 41.85, respectively. In contrast, the control plants, (no nitrogen and phosphorus), exhibited the lowest values across all parameters. Plant height in the control group reached only 39.2 cm at flowering and 43.12 cm during fruit development. Similarly, leaf area was limited to 39.2 cm^2 and 43.12 cm^2, total dry matter was 8.25 g $plant^{-1}$ and 28.14 g $plant^{-1}$ and SPAD values were 30.35 and 32.14 during flowering and fruit development, respectively.

Effect of foliar spray of nano DAP on quality of tomato

Ascorbic acid (mg 100 g^{-1}), firmness (Newton), total soluble solids (°Brix) and titratable acidity (% of citric acid) in ripened tomatoes are crucial indicators of both marketability and nutritional value, making them essential parameters for assessing tomato quality. The evaluation of quality traits in tomatoes treated with nano DAP showed significant variations among the treatments, particularly in ascorbic acid (mg 100 g^{-1}), firmness (Newton), total soluble solids (°Brix) and titratable acidity (% of citric acid) shown in Table 2.

Table 1. Effect of nano DAP on plant height, dry matter, chlorophyll, leaf area and soluble protein in tomato at 30 and 50 DAT

Treatments	Plant height (cm)		Total dry matter (g $plant^{-1}$)		Chlorophyll index (SPAD)		Leaf area (cm^2)	
	Flowering stage	Fruit development	Flowering stage	Fruit development	Flowering stage	Fruit development	Flowering stage	Fruit development
Recommended dose of fertilizer (RDF) + all package of practices	47.50^{a}	51.42^{a}	12.40^{b}	36.12^{ab}	37.15^{ab}	38.15^{ab}	542.30^{ab}	945.30^{ab}
50% RDNP (recommended dose of nitrogen and phosphorus)	39.50^{b}	43.50^{bc}	8.47^{d}	28.45^{d}	30.45^{cd}	32.10^{c}	352.77^{de}	820.12^{d}
50% RDNP + 2 sprays of nano DAP at 0.7 % during flowering and fruit development	45.30^{a}	49.49^{b}	11.72^{bc}	35.45^{ab}	36.85^{ab}	37.45^{b}	492.84^{c}	887.58^{bcd}
75% RDNP (recommended dose of nitrogen and phosphorus)	41.00^{ab}	44.12^{c}	9.10^{d}	30.72^{cd}	34.18^{bc}	35.10^{bc}	392.54^{d}	835.26^{cd}
75% RDNP + 2 sprays of nano DAP at 0.7 % during flowering and fruit development	48.90^{a}	54.31^{a}	13.80^{a}	37.85^{a}	40.05^{a}	41.85^{a}	585.96^{a}	987.05^{a}
75% recommended N through fertilizer + 2 sprays of DAP at 2% during flowering and fruit development	44.60^{ab}	48.45^{b}	11.82^{bc}	35.25^{ab}	36.95^{ab}	37.19^{b}	525.48^{bc}	930.24^{abc}
50% recommended N through fertilizer + 2 sprays of DAP at 2% during critical growth stages	43.00^{ab}	46.12^{bc}	10.72^{c}	33.85^{bc}	35.15^{b}	36.95^{b}	478.23^{c}	845.48^{cd}
Control (no nitrogen and phosphorus)	39.20^{c}	43.12^{d}	8.25^{d}	28.14^{d}	30.35^{d}	32.14^{c}	320.59^{e}	806.35^{d}
CD ($p \leq 0.05$)	**6.031**	**5.058**	**1.155**	**3.585**	**3.818**	**3.943**	**49.231**	**96.221**

Values are presented as means ± SD. Bars labeled with different letters represent significant differences, determined by Duncan's multiple range test ($p \leq 0.05$).

Among the treatment combinations, the highest value for ascorbic acid (mg 100 g^{-1}), firmness (Newton) and total soluble solids (°Brix) were recorded in the treatment comprising 75% RDNP combined with two sprays of nano DAP at 0.7% during flowering and fruit development (T5). Conversely, the control plants exhibited the lowest values for ascorbic acid (25.70 mg 100 g^{-1}), firmness (8.85 Newtons) and total soluble solids (4.22 °Brix).

Interestingly, the control plants recorded the highest titratable acidity at 0.54% citric acid, while fruits from the treatment involving 75% RDNP combined with two foliar sprays of nano DAP at 0.7% during fruit development showed significantly lower titratable acidity at 0.39% citric acid (Table 2).

Effect of foliar spray of nano DAP on yield parameters of tomato

The foliar application of nano DAP significantly influenced yield-attributing traits including number of flowers per plant, number of fruits per plant, fruit set percentage and fruit yield (kg $plant^{-1}$) per plant, significantly observed among the treatments. The treatment T5-75% RDNP combined with two foliar sprays of nano DAP at 0.7% during flowering and fruit development-recorded the highest values for the number of flowers per plant, the number of fruits per plant and fruit yield (kg $plant^{-1}$) given in Table 3. The minimum number of flowers per plant, fruits per plant and fruit yield (kg $plant^{-1}$) were recorded in the control plants.

Effect of foliar spray of nano DAP on gas exchange parameters

The concentration of CO_2 in the intercellular spaces of a leaf (Ci) is a crucial factor influencing the flux of CO_2 into the leaf during photosynthesis. Gas exchange parameters, including the photosynthetic rate (μ mol CO_2 $m^{-2}s^{-1}$), transpiration rate (m mol H_2O m^{-2} s^{-1}) and stomatal conductance (mol H_2O $m^{-2}s^{-1}$), were significantly increased in the T5 - 75% RDNP combined with two sprays of nano DAP at 0.7% during the flowering and fruit development stages. The lowest gas exchange parameters were observed in T8 (control) as showed in Fig. 1.

Effect of foliar spray of nano DAP on leaf soluble protein of tomato

Nano DAP, due to its high nutrient availability and efficient absorption facilitated by its nano-sized particles, enhances the uptake of essential nutrients like N. The increased N availability directly promotes the synthesis of soluble proteins in the leaves, as N is an essential component of amino acids and proteins. Among the treatments, the highest leaf-soluble protein content was observed in the treatment of 75% RDNP combined with two sprays of nano DAP at 0.7% during the flowering and fruit development stages. The same treatment T8 observed the lowest soluble protein (Fig. 1).

Discussion

Nano fertilizers provide efficient nutrient delivery, reducing yield losses and promoting plant development through enhanced nutrient absorption (26). Nitrogen plays a crucial role in the morphological development of plants, enhancing the growth of leaves that contribute more effectively to yield. Elevated nitrogen levels lead to improved vegetative traits (22). As an essential component of amino acids and proteins, nitrogen is vital for cell division and growth, whereas phosphorus is critical for energy

Table 2. Effect of nano DAP on ascorbic acid firmness, total soluble solids, titratable acidity in tomato at 30 and 50 DAT

Treatments	Ascorbic acid (mg 100 g^{-1})	Total soluble solids (°Brix)	Firmness (Newton)	Titratable acidity (% of citric acid)
Recommended dose of fertilizer (RDF) + all package of practices	33.25^{ab}	5.32^{ab}	10.15^{ab}	0.42^{de}
50% RDNP (recommended dose of nitrogen and phosphorus)	26.15^{de}	4.62^{cd}	9.16^{bc}	0.52^{ab}
50% RDNP + 2 sprays of Nano DAP at 0.7% during flowering and fruit development	30.27^{bc}	5.22^{ab}	10.07^{ab}	0.44^{cde}
75% RDNP (recommended dose of nitrogen and phosphorus)	27.35^{cde}	4.93^{bc}	9.68^{bc}	0.48^{bc}
75% RDNP + 2 sprays of Nano DAP at 0.7% during flowering and fruit development	35.66^{a}	5.52^{a}	11.08^{a}	0.39^{e}
75% recommended N through fertilizer + 2 sprays of DAP at 2% during flowering and fruit development	29.27^{cd}	5.19^{ab}	10.05^{ab}	0.45^{cd}
50% recommended N through fertilizer + 2 sprays of DAP at 2% during critical growth stages	27.29^{cde}	5.06^{abc}	9.66^{bc}	0.46^{cd}
Control (no nitrogen and phosphorus)	25.70^{e}	4.22^{d}	8.85^{c}	0.54^{a}
CD ($p \leq 0.05$)	**3.199**	**0.544**	**1.071**	**0.054**

Values are presented as means ± SD. Bars labeled with different letters represent significant differences, determined by Duncan's multiple range test ($p \leq 0.05$).

Table 3. Effect of nano DAP on yield parameters of tomato

Treatments	Number of flowers per plant	Number of fruits per plant	Yield (kg $plant^{-1}$)	Fruit set percentage
Recommended dose of fertilizer (RDF) + all package of practices	25.4^{ab}	18.5^{b}	1.20^{ab}	72.83^{ab}
50% RDNP (recommended dose of nitrogen and phosphorus)	23.1^{de}	16.2^{c}	1.08^{de}	70.13^{bc}
50% RDNP + 2 sprays of nano DAP at 0.7% during flowering and fruit development	25.2^{abc}	18.3^{b}	1.19^{b}	72.62^{bc}
75% RDNP (recommended dose of nitrogen and phosphorus)	23.5^{cd}	16.3^{c}	1.09^{cde}	69.15^{c}
75% RDNP + 2 sprays of Nano DAP at 0.7% during flowering and fruit development	28.2^{a}	23.1^{a}	1.47^{a}	81.84^{a}
75% recommended N through fertilizer +2 sprays of DAP at 2% during flowering and fruit development	24.7^{abc}	17.5^{bc}	1.15^{bc}	70.65^{bc}
50% recommended N through fertilizer + 2 sprays of DAP at 2% during critical growth stages	24.6^{bcd}	17.4^{bc}	1.14^{bcd}	70.81^{c}
Control (no nitrogen and phosphorus)	18.5^{e}	12.4^{d}	0.95^{e}	67.03^{bc}
CD ($p \leq 0.05$)	**2.262**	**1.836**	**0.119**	**8.078**

values are presented as means ± SD. Bars labeled with different letters represent significant differences, determined by Duncan's multiple range test ($p \leq 0.05$).

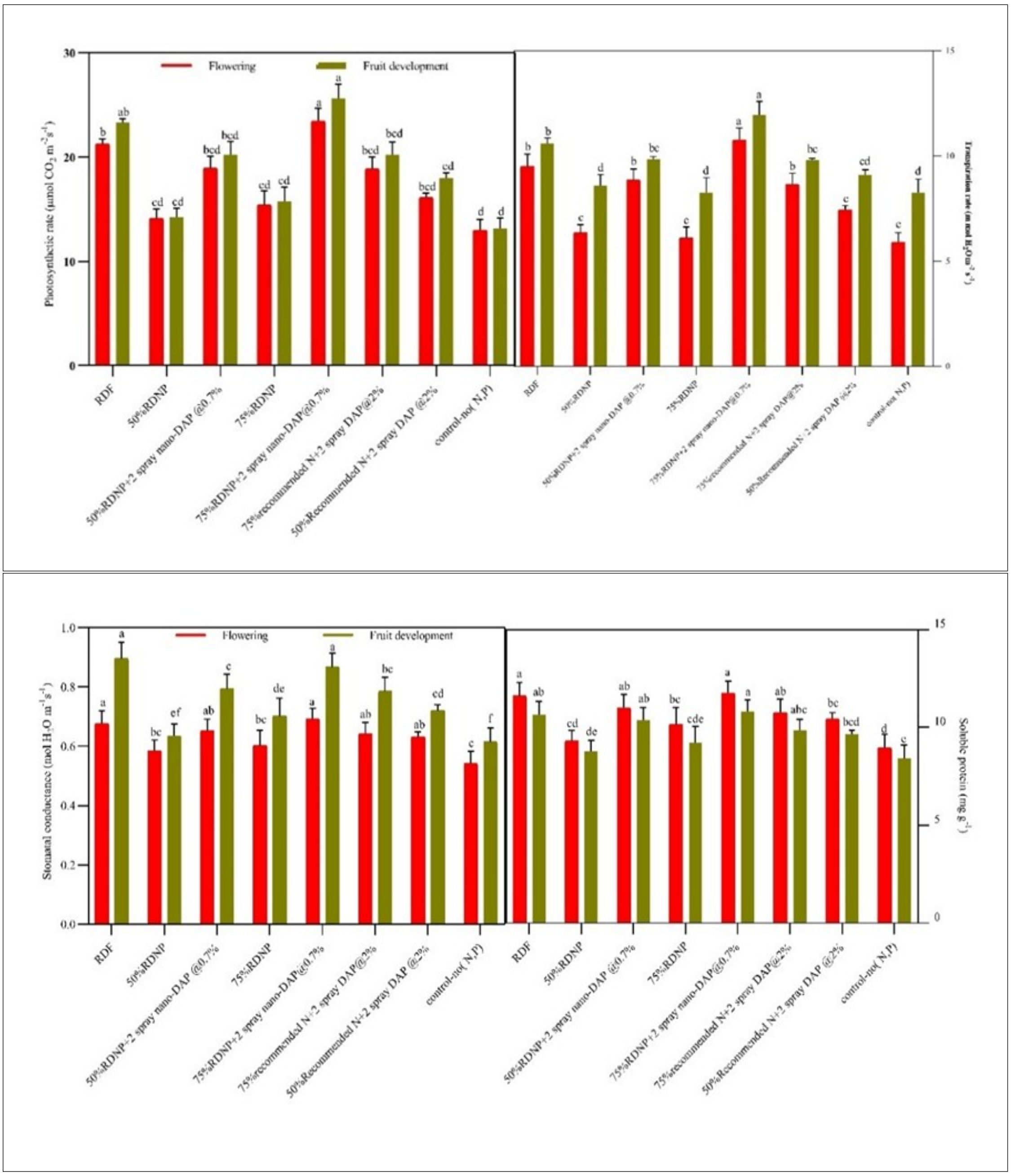

Fig. 1. Effect of Nano DAP on gas exchange on photosynthetic rate, transpiration rate, stomatal conductance, leaf soluble protein in tomato at 30 and 50 DAT. Values are presented as means ± SD. Bars labeled with different letters represent significant differences, determined by Duncan's multiple range test ($p \leq 0.05$).

transfer, root development and flowering. By improving the availability of these nutrients, nano DAP stimulates cellular processes such as auxin production and enzyme activity, which are closely associated with increased plant height (18). The combined use of conventional fertilizers and nano DAP, applied to the soil and as a foliar spray, likely contributed to the significant increase in plant height by enhancing auxin metabolism and enzyme activity, respectively. These findings align with the other study (27).

The highest chlorophyll index can be attributed to the provision of essential elements such as nitrogen, phosphorus and potassium. N is a core component of chlorophyll molecules and is essential for the formation of the photosynthetic apparatus, including enzymes like rubisco, which drive carbon fixation. P plays a vital role in energy transfer through the formation of ATP (adenosine triphosphate), which is crucial for the light-dependent reactions of photosynthesis. Potassium (K) helps regulate stomatal opening, enhancing CO_2 uptake and also improves enzyme activation and the transport of photosynthetic products (28). The availability of phosphorus is essential for key physiological processes such as photosynthesis, respiration and energy transfer (29).

Nanoparticles can penetrate plant cells, sustaining their survival and supplying meristematic tissues with the necessary resources for growth and division, thereby activating metabolism, including photosynthesis and chlorophyll pigment production (30). Nano fertilizers improve plant vitality and accelerate photosynthesis (31). Foliar spraying has been shown to significant increase nutrient availability and crop yield (32). The application of nano DAP as a foliar spray at different growth stages significantly boosted wheat yield, yield components, leaf area, biomass and phosphorus content, while using 75% less input compared to traditional commercial DAP. Similarly, nano urea treatment resulted in the highest dry matter due to enhanced nitrogen availability and reduced ammonia loss (33). The application of nano DAP enhanced chlorophyll pigment production and promoted the activity of ribulose-1,5-bisphosphate carboxylase (rubisco), which in turn stimulated the photosynthetic rate in plants. Nitrogen is crucial for chlorophyll synthesis, which directly affects the plant's light-harvesting capacity, while phosphorus is essential for energy transfer through ATP and NADPH (nicotinamide adenine dinucleotide phosphate), necessary for the Calvin cycle. By improving the availability of these elements, nano DAP enhances the synthesis of essential proteins and enzymes, such as rubisco, which facilitate carbon fixation. This ultimately leads to improved photosynthetic efficiency, higher energy production and increased plant growth and yield (34).

The photosynthetic system is the backbone of plant function; therefore, any improvement in photosynthesis due to nano DAP will also lead to increases in related parameters such as stomatal conductance (gs), transpiration rate (E) and intercellular CO_2 concentration (Ci). Gas exchange parameters, including photosynthetic rate (A), stomatal conductance (gs) and transpiration rate (E), are crucial in determining overall plant health and yield. These physiological processes are interconnected and directly influence plant growth, productivity and water-use efficiency. Photosynthesis (A) is the process by which plants convert light energy into chemical energy, directly driving biomass accumulation and yield. Higher photosynthetic rates are positively correlated with improved plant health and higher crop productivity. Stomatal conductance (gs) regulates the exchange of gases, particularly CO_2 and water vapor, between the plant and the environment. Optimal stomatal regulation allows sufficient CO_2 uptake for photosynthesis while minimizing excessive water loss, which is essential for maintaining turgor and preventing drought stress. Efficient transpiration (E) further aids in cooling the plant and transporting nutrients, supporting metabolic functions and promoting overall growth (29). Similarly, the use of nano-zinc fertilizers has been shown to improve stomatal conductance and transpiration rate in tomato plants, enhancing their drought tolerance and water-use efficiency (35).

The incorporation of nano-silicon in rice cultivation has been shown to increase net photosynthetic rate, stomatal conductance and transpiration, ultimately leading to improved grain yield and quality (36). The use of nano-phosphorus fertilizers has been found to significantly enhance the photosynthetic rate in cabbage plants, resulting in greater biomass production and improved overall plant vigour (37). The application of nano-iron has been reported to improve membrane stability, enhance protein content and alter pigment levels, such as chlorophyll content (SPAD), in numerous studies. The presence of nano-iron contributes to physiological improvements by enhancing chlorophyll synthesis, as iron is a vital cofactor in chlorophyll production and electron transport during photosynthesis. Its nanoscale form ensures efficient uptake and delivery, leading to improved photosynthetic rates, plant growth and nutrient use efficiency (38).

As iron is essential for numerous reactions, including those in the photosynthetic electron transport chain, it may contribute to increased membrane stability and protein content, along with proline and chlorophyll levels, in plants under heat stress. Soluble proteins are crucial for plant health and yield as they are key components involved in essential physiological processes such as enzyme activity, stress response and photosynthesis. These proteins, including enzymes like rubisco, play a central role in carbon fixation during photosynthesis, directly influencing biomass accumulation and plant productivity. Additionally, soluble proteins are involved in stress responses, helping plants adapt to environmental stresses such as drought or salinity by regulating osmotic balance and protecting cellular structures. The overall level of soluble proteins is often linked to a plant's metabolic health and growth potential, with reductions in protein levels typically associated with impaired physiological function and lower yields. Maintaining adequate soluble protein levels ensures optimal metabolic activity, contributing to plant vigor and high agricultural output (39).

The foliar application of nano-Fe oxide increased chlorophyll content, enhanced antioxidant enzyme activities and promoted the accumulation of soluble proteins and carbohydrates in wheat (40). Foliar application of nano-DAP also resulted in significant improvements in fruit quality, including higher total soluble solids (TSS), increased titratable acidity (TA), improved firmness and elevated ascorbic acid content. The integration of nano-scale particles in a multi-micronutrient formulation may have enhanced nutrient uptake and translocation within the plant, leading to better nutrient utilization for biochemical activities. TSS and firmness are essential factors influencing the marketability and nutritional value of tomatoes. TSS, which primarily measures sugar content, directly impacts the flavor and sweetness of tomatoes, enhancing their market appeal. Higher TSS levels improve taste and overall consumer satisfaction, contributing to increased market demand. Firmness, on the other hand, affects the texture, shelf life and transportability of tomatoes. Firmer tomatoes are more resistant to damage during handling and storage preserving their quality and appearance over time. Researches indicate that high TSS and firmness are critical characteristics for consumer preference and commercial success in the tomato industry (41). This, in turn, has positive effects on quality parameters such as TSS, ascorbic acid content, firmness and titratable acidity (42). Similar findings were reported , where foliar treatments combining zinc (Zn) and boron (B) also significantly enhanced fruit quality, resulting in higher TSS, increased TA and elevated vitamin C content (43). The increase in TSS content in fruits may be attributed to growth-promoting substances that likely accelerated the synthesis of carbohydrates, vitamins and other quality traits.

Ascorbic acid (vitamin C) is essential for both the nutritional value and marketability of tomatoes. Tomatoes, being a rich source of vitamin C, contribute to human health by boosting immunity and providing antioxidants. Higher ascorbic acid content enhances their appeal as a nutritious food and improves marketability by increasing quality and shelf life. The antioxidant properties of vitamin C help reduce spoilage and maintain freshness, making tomatoes rich in ascorbic acid more attractive to consumers. Studies have shown that tomatoes with high vitamin C content are in greater demand in the fresh food market (44).

An increase in protein and ascorbic acid content in French beans was observed after the application of nano-multi micronutrients combined with the standard fertilizer dose for French bean cultivation (45). The ascorbic acid and titratable acidity levels in tomato fruits were significantly higher in plants treated with ZnO nanoparticles (ZnO-NPs) compared to those treated with conventional Zn fertilizer (46). Foliar application of 50 ppm ZnO-NPs resulted in a 23% increase in titratable acidity compared to the control group. Moreover, foliar application of 100 ppm ZnO-NPs led to notable improvements in ascorbic acid levels, titratable acidity, photosynthetic characteristics and enzymatic activities.

A similar finding was reported where fruit firmness in tomatoes, an important quality parameter closely related to the ripening stage, was discussed (47). During the ripening stage, tomatoes often display their best flavour but become more delicate and prone to damage. To extend their shelf life and protect them from handling damage, it is preferable to harvest tomatoes earlier. Nano zinc particles have been shown to significantly improve tomato fruit firmness and extend shelf life.

The number of flowers and fruits per plant is a crucial factor in improving crop yield. An increase in the number of flowers and fruits may result from the balanced NPK content of the growing medium when treated with nano DAP. The results indicate that the foliar application of nano chitosan may have enhanced phosphorus availability and uptake, leading to improved bud break and increased flowering in strawberry plants (48). This increase in vegetative growth, flowering and fruiting attributes from the application of nano chitosan likely contributed to other physiological processes, such as the efficient translocation of photo assimilates from source to sink tissues, resulting in greater plant length and width.

The impact of nano DAP on increasing fruit yield can be attributed to its enhanced nutrient efficiency. The smaller particle size of nano DAP provides a larger surface area, enabling more effective absorption and utilization of key nutrients like nitrogen and phosphorus by tomato plants. This improved nutrient uptake supports stronger growth and more robust flowering, ultimately leading to the highest fruit yield. These findings are consistent with the results which observed that the application of nano fertilizer increased cabbage yield by 38-42% and potato yield by 35-40% compared to the control (49).

Conclusion

This study highlights the significant benefits of using nano DAP in tomato cultivation. Nano DAP, particularly when combined with 75% of RDNP and supplemented with two foliar sprays during critical growth stages, such as flowering and fruit development, has demonstrated significant improvements in plant height, chlorophyll content, total dry matter production, total soluble sugars and fruit yield. The superior performance of nano DAP-treated plants can be attributed to its efficient nutrient delivery system, which enhanced the uptake of essential nutrients like nitrogen and phosphorus, critical for plant growth, photosynthesis and overall plant health. The results indicate that nano DAP not only improves tomato yield and quality but also offers a long-term solution for nutrient management in agriculture.

Utilization of nano DAP fertilizer can improve resource efficiency, reduces environmental impact and boosts agricultural productivity, making it a valuable tool for advancing farming practices. As a nano-fertilizer, nano-DAP provides superior bioavailability and efficiency compared to conventional fertilizers. This is particularly valuable in light of depleting natural phosphorus reserves. Its applications supports sustainable agricultural practices by minimizing fertilizer inputs while maximizing crop yields, addressing the growing global demand for food production as the global population continues to rise.

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Authors' contributions

SK and MR conceptualized and conducted the study. MR, AS, MP and VS validated the data. SK and MR performed the statistical analysis, data visualization and drafting of the original manuscript. MR, AS, MP and VS contributed to the review and editing of the final manuscript. All co-authors reviewed the final version and approved the manuscript for submission.

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In the process of preparing this work, the authors used Grammarly to improve grammar, punctuation and spelling for better readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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