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EFFECTS OF APPLICATION OF NANO DAP ON MAJOR NUTRIENT AVAILABILITY AND UPTAKE BY TEA PLANTS

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ABSTRACT

The present investigation was conducted from March to December 2024 to evaluate the effect of Nano Diammonium Phosphate (Nano DAP) on nutrient availability and nutrient uptake in tea (*Camellia sinensis* L.). The experiment was carried out in the Experimental Garden for Plantation Crops, Assam Agricultural University, Jorhat, using mature tea plants of clone TV 23. The trial was laid out in a Randomized Block Design (RBD) with five treatments and four replications. Nano DAP was applied as a foliar spray at a concentration of 3 mL L^{-1}, allowing nanoparticles to penetrate through stomata and other leaf pores, thereby enhancing nutrient absorption and utilization. The study evaluated soil available nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O), along with leaf nutrient content and uptake of N, P_2O_5 and K_2O by tea plants. The results revealed significant differences among the treatments. Treatments **T_2** (recommended dose of N, P_2O_5 and K_2O + three foliar sprays of Nano DAP @ 3 mL L^{-1}) and **T_3** (recommended dose of N and K_2O + 75% of the recommended dose of P_2O_5 + three foliar sprays of Nano DAP @ 3 mL L^{-1}) recorded significantly higher soil nutrient availability and nutrient uptake than the conventional fertilizer treatment (**T_1**) receiving the recommended dose of N, P_2O_5 and K_2O alone. The performance of T_3 was statistically comparable with T_2, indicating that 25% of the recommended basal phosphorus fertilizer could be successfully replaced by foliar application of Nano DAP without adversely affecting nutrient availability or uptake. The findings demonstrate that Nano DAP is an effective nutrient management strategy for tea cultivation, improving nutrient use efficiency while reducing dependence on conventional phosphatic fertilizers. Therefore, Nano DAP has the potential to serve as an economically viable and environmentally sustainable alternative for enhancing fertilizer use efficiency and promoting sustainable tea production.

Key words : DAP, Nano, Foliar, Tea cultivation, Potassium.

Introduction

Tea (*Camellia sinensis* (L.) O. Kuntze) is one of the most important perennial plantation crops and the second most consumed beverage in the world after water. It is cultivated in more than 60 countries and plays a significant role in the economy of several tea-producing nations. India is the second-largest producer of tea globally and the industry contributes substantially to employment generation, foreign exchange earnings and rural livelihoods. During 2023–24, India produced approximately 1291.49 million kg of tea, with exports contributing nearly 226.98 million kg, demonstrating the economic importance of the crop (Jagadeesh *et al.*, 2024). Sustainable tea production depends largely on efficient nutrient management because the continuous harvesting of tender shoots results in considerable removal of plant nutrients from the soil. Therefore, maintaining adequate soil fertility through balanced fertilization is essential for sustaining tea yield, quality and long-term productivity. Among the seventeen essential plant nutrients, nitrogen (N), phosphorus (P) and potassium (K) are the primary macronutrients required in relatively

large quantities for normal growth and development of tea plants. Fertilizer recommendations in tea vary depending on yield level, soil fertility, climatic conditions, clone, bush age and management practices. Nitrogen is indispensable for chlorophyll synthesis, amino acid formation, protein metabolism and photosynthesis, thereby directly influencing vegetative growth and shoot production. Adequate nitrogen nutrition also enhances the synthesis of quality-related compounds such as theanine and catechins, improving the quality of manufactured tea (Bernard and Habash, 2009; Ma *et al.*, 2021; Ruan *et al.*, 2010). Phosphorus plays a vital role in root development, energy transfer, nucleic acid synthesis and cell division, while potassium regulates enzyme activation, osmotic balance, carbohydrate translocation and stress tolerance. Tea removes considerable quantities of these nutrients through repeated harvesting, with approximately 5.0 kg nitrogen, 1.0 kg phosphate and 2.0 kg potash being removed for every quintal of made tea produced (Barooah and Phukan, 2020). Consequently, balanced fertilization is indispensable for maintaining nutrient reserves in the soil and sustaining crop productivity. Despite the widespread use of conventional chemical fertilizers, their nutrient use efficiency remains relatively low. A significant proportion of applied nitrogen is lost through volatilization, leaching, denitrification and runoff before it becomes available to plants, resulting in poor fertilizer use efficiency and environmental pollution. Continuous and excessive application of nitrogenous fertilizers also contributes to soil acidification, greenhouse gas emissions and contamination of water bodies (Rebello *et al.*, 2022). Likewise, phosphorus availability is often limited in acidic tea-growing soils because a major fraction of applied phosphate becomes fixed by iron and aluminium oxides, making it unavailable for plant uptake. Studies have shown that less than 15% of the applied phosphorus fertilizer is utilized by crops during the year of application (Adnan *et al.*, 2003; Brady and Weil, 1984). Long-term fertilizer experiments in tea have further demonstrated that optimum crop response to nitrogen is achieved only when phosphorus availability is adequate, highlighting the importance of balanced nutrient management (Biswas *et al.*, 1984; Sharma *et al.*, 1977; Wickremaratne, 1971).

Recent advances in nanotechnology have opened new opportunities for improving fertilizer use efficiency through the development of nano fertilizers. Owing to their extremely small particle size, large surface area and controlled nutrient release characteristics, nano fertilizers facilitate rapid nutrient absorption and efficient translocation within plant tissues while minimizing nutrient losses to the environment. Nano Diammonium Phosphate (Nano DAP), developed as a nano-formulation of diammonium phosphate, is applied as a foliar spray, enabling nutrients to enter the plant through stomata and other leaf openings. This mode of application reduces nutrient fixation in soil, enhances nutrient use efficiency and offers the possibility of reducing the basal application of conventional phosphatic fertilizers. Previous studies have demonstrated that nano fertilizers improve nutrient uptake, growth and productivity while reducing fertilizer requirements (Zulfiqar *et al.*, 2019). Similarly, foliar nutrient application has been reported to provide rapid nutrient absorption, particularly under conditions where nutrient availability from the soil is limited, and serves as an efficient supplementary method of fertilizer application (Sarkar *et al.*, 2021).

Recent investigations have also reported the beneficial effects of Nano DAP on soil properties, nutrient availability and nutrient uptake in agricultural crops (Chamuah *et al.*, 2023 and Dhansil *et al.*, 2018). In tea, foliar application of nano fertilizers has shown encouraging results in improving leaf nutrient status and quality parameters, indicating their potential for sustainable nutrient management (Saikia *et al.*, 2024). Although nano fertilizers have shown promising results in several agricultural crops, information regarding the use of Nano DAP in tea cultivation remains limited. In particular, there is insufficient evidence on whether Nano DAP can improve soil nutrient availability and nutrient uptake while reducing the recommended basal application of phosphatic fertilizers without compromising nutrient status. Such information is essential for developing sustainable fertilizer management strategies that enhance nutrient use efficiency, reduce production costs and minimize the environmental impact of excessive fertilizer use in tea plantations.

Therefore, the present investigation was undertaken to evaluate the effect of foliar application of Nano DAP on soil nutrient availability and nutrient uptake in mature tea (*Camellia sinensis* L.) plants. The study also aimed to determine whether foliar application of Nano DAP could successfully replace 25% of the recommended basal phosphorus fertilizer while maintaining nutrient availability and nutrient uptake under the agro-climatic conditions of Assam. The findings are expected to provide scientific evidence for the adoption of Nano DAP as an efficient and environmentally sustainable nutrient management strategy in tea cultivation.

Materials and Methods

Experimental site and design

The field experiment was conducted from February

Table 1 : Treatment details.

Treatment	Description
T_1	Recommended dose of N, P_2O_5 and K_2O (100:25:75 kg ha^{-1})
T_2	Recommended dose of N, P_2O_5 and K_2O + three foliar sprays of Nano DAP @ 3 mL L^{-1}
T_3	Recommended dose of N and K_2O + 75% recommended P_2O_5 + three foliar sprays of Nano DAP @ 3 mL L^{-1}
T_4	Recommended dose of N and K_2O + 50% recommended P_2O_5 + three foliar sprays of Nano DAP @ 3 mL L^{-1}
T_5	Recommended dose of N and K_2O + 25% recommended P_2O_5 + three foliar sprays of Nano DAP @ 3 mL L^{-1}

to December 2024 at the Experimental Garden for Plantation Crops (Section 2A), Department of Tea Husbandry and Technology, Assam Agricultural University, Jorhat, Assam, India. The experimental site comprised mature tea bushes of clone TV 23 planted at a spacing of 105 cm × 70 cm.

The experiment was laid out in a Randomized Block Design (RBD) consisting of five treatments and four replications.

Fertilizer application

The recommended fertilizer dose for mature tea was 100:25:75 kg N:P_2O_5:K_2O ha^{-1}, supplied through urea, single super phosphate (SSP) and muriate of potash (MOP). Nitrogen and potassium fertilizers were applied in two splits, with 60% applied during April and 40% during August 2024, whereas the entire dose of SSP was applied as a basal application during April 2024.

Nano DAP (IFFCO, India), containing 8.0% nitrogen (w/v) and 16.0% phosphorus (P_2O_5, w/v), was applied as a foliar spray at 3 mL L^{-1} during April, July and October 2024.

Soil sampling and initial soil properties

Composite soil samples were collected during February (before treatment application), July and December 2024 from each treatment using a soil auger. Samples were collected in a zigzag pattern from each replication at depths of 0–30 cm (topsoil) and 30–45 cm (subsoil). The collected samples were air-dried, ground, passed through a 2-mm sieve and stored for laboratory analysis.

The initial physico-chemical properties of the experimental soil are presented in Table 1a.

Table 1a : Initial physico-chemical properties of the experimental soil

Parameter	Value	Method
Texture	Sandy loam	International Pipette method (Piper, 1966)
Soil pH	4.40	Glass electrode pH meter
Organic carbon (%)	1.20	Walkley and Black (1934)
Available N (kg ha^{-1})	288.00	Subbiah and Asija (1956)
Available P_2O_5 (kg ha^{-1})	27.80	Bray and Kurtz (1945)
Available K_2O (kg ha^{-1})	182.78	Jackson (1973)

Estimation of soil nutrient availability

Soil available nitrogen was estimated by the alkaline permanganate method described by Subbiah and Asija (1956). Available phosphorus was determined using the Bray I extraction method (Bray and Kurtz, 1945), while available potassium was estimated by flame photometry following the procedure of Jackson (1973). The nutrient contents were expressed as kg ha^{-1}.

Estimation of leaf nutrient content

Freshly plucked third leaves were collected from each treatment, oven dried at 40°C, ground into fine powder and analysed for nutrient content. Leaf nitrogen was determined by the Kjeldahl method following Jackson (1973). Leaf phosphorus was estimated colorimetrically after di-acid digestion using the vanado-molybdate yellow colour method, whereas leaf potassium was determined using a flame photometer as described by Jackson (1973). Nutrient concentrations were expressed as percentage of dry leaf weight.

Nutrient uptake

Nitrogen, phosphorus and potassium uptake by tea plants were calculated using leaf nutrient concentration and corresponding dry matter production. The uptake values were expressed as kg ha^{-1}.

Statistical analysis

The experimental data were analysed using analysis of variance (ANOVA) appropriate for a Randomized Block Design following the procedure described by Gomez and Gomez (1984). Treatment means were compared using the critical difference (CD) test at the 5% level of significance ($P \leq 0.05$). Statistical analyses were performed using Microsoft Excel 2021.

Results and Discussion

Effect of Nano DAP on soil nutrient availability

Soil available nitrogen

The application of Nano DAP significantly influenced the available nitrogen status of the experimental soil during both July and December 2024 (Table 2). The highest soil available nitrogen was recorded in the recommended fertilizer treatment (T_1), with values of 320.41 kg ha^{-1} in July and 256.81 kg ha^{-1} in December. In contrast, the lowest soil available nitrogen was observed in T_2 (306.74 and 241.69 kg ha^{-1} during July and December, respectively), followed closely by T_3 (309.49 and 243.12 kg ha^{-1}). The differences between T_2 and T_3 were statistically non-significant, whereas both treatments differed significantly from T_1. Treatment T_5 recorded intermediate values, remaining significantly higher than T_2, but lower than T_1.

The reduction in residual soil nitrogen under T_2 and T_3 may be attributed to greater nitrogen uptake by tea plants following foliar application of Nano DAP. Tea is a continuously harvested crop with frequent removal of young shoots, resulting in a constant demand for nitrogen throughout the growing season. Enhanced foliar nutrient absorption probably increased nitrogen utilization by the crop, thereby reducing the quantity of available nitrogen remaining in the soil. Similar observations on improved nitrogen use efficiency following balanced fertilization have been reported by Zhang *et al.* (2010), while Grunes (1959) also reported that improved nitrogen nutrition enhances phosphorus acquisition and overall nutrient utilization by plants.

Soil available phosphorus (P_2O_5)

Soil available phosphorus was significantly affected by different fertilizer treatments (Table 3). Treatment T_1 recorded the highest available phosphorus content, with 30.99 kg ha^{-1} during July and 25.59 kg ha^{-1} during December. Among the Nano DAP treatments, T_2 and T_3 recorded comparable phosphorus availability and were statistically at par. The lowest available phosphorus was observed in T_5, where only 25% of the recommended basal phosphorus dose was applied.

The comparatively lower residual phosphorus recorded in T_2 and T_3 indicates greater phosphorus utilization by tea plants rather than nutrient deficiency. Foliar application of Nano DAP improves phosphorus availability to the plant by supplying nutrients directly through the leaf surface, thereby enhancing nutrient use efficiency. However, when the basal phosphorus dose was reduced beyond 25% (T_4 and T_5), the beneficial effect of Nano DAP was less pronounced, suggesting that an adequate basal phosphorus supply remains necessary for optimum nutrient uptake. This response is particularly relevant in the acidic soils of Assam, where phosphorus fixation by iron and aluminium oxides substantially reduces phosphorus availability. Adnan *et al.* (2003) and Brady and Weil (1984) reported that only a small proportion of applied phosphorus remains available for crop uptake in acidic soils because of fixation reactions. Similar positive interactions between nitrogen and phosphorus have also been reported in long-term tea fertilization studies by Biswas *et al.* (1984) and Sharma *et al.* (1977).

Table 2 : Soil available nitrogen (kg/ha) as influenced by application of Nano DAP based fertilizers in July and December, 2024.

Treatments	Soil available N (kg/ha)	
	July, 2024	December, 2024
T_1	320.41	256.81
T_2	306.74	241.69
T_3	309.49	243.12
T_4	311.66	246.72
T_5	317.92	252.19
CD	5.06	4.96
SE(d)	2.32	2.27

Table 3 : Soil available phosphate (kg/ha) as influenced by application of Nano DAP based fertilizers in July and December, 2024.

Treatments	Soil available P_2O_5 (kg/ha)	
	July, 2024	December, 2024
T_1	30.99	25.59
T_2	28.01	21.16
T_3	27.91	21.56
T_4	27.61	23.61
T_5	26.44	22.01
CD	1.47	1.56
SE(d)	0.68	0.71

Soil available potassium (K_2O)

The available potassium content of the soil also differed significantly among treatments (Table 4). The highest residual potassium content was recorded under T_1 (237.50 and 197.13 kg ha^{-1} during July and December, respectively), whereas the lowest values were obtained in T_2 (226.33 and 185.56 kg ha^{-1}). Treatment T_3 showed potassium levels statistically comparable with T_2, while

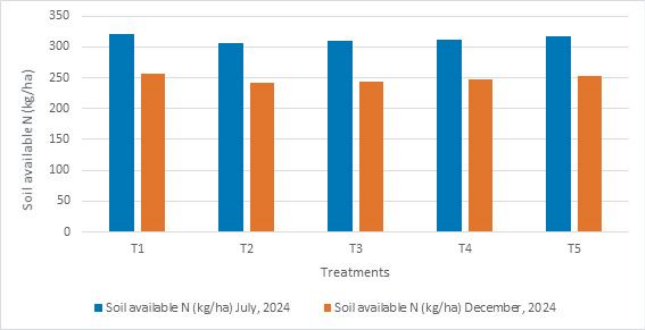

Fig. 1 : Soil Available Nitrogen (Kg/ha) as influenced by Application of Nano DAP based Fertilizers in July and December, 2024.

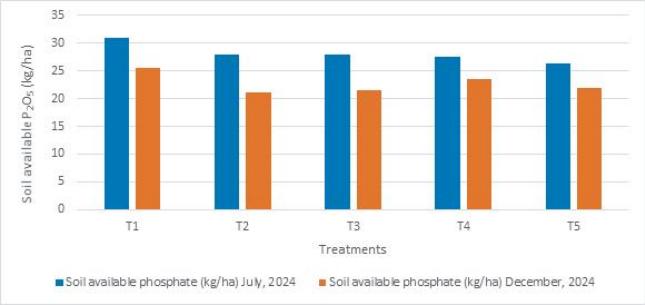

Fig. 2 : Soil Available Phosphate (Kg/ha) as influenced by Application of Nano DAP based Fertilizers (July, 2024 and December, 2024).

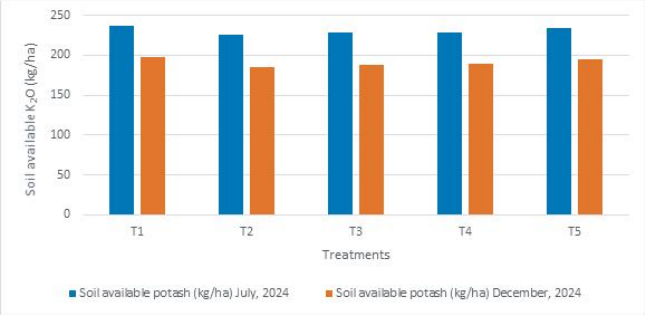

Fig. 3 : Soil Available Potash (Kg/ha) as influenced by Application of Nano DAP based Fertilizers (July, 2024 and December, 2024).

T_5 recorded values closer to those of the recommended fertilizer treatment.

The decline in residual soil potassium observed under T_2 and T_3 can be attributed to increased potassium uptake by tea plants resulting from improved nutrient absorption following Nano DAP application. Potassium plays an essential role in enzyme activation, carbohydrate translocation and stomatal regulation, and its uptake is closely associated with nitrogen metabolism. Improved nitrogen nutrition enhances potassium utilization, leading to greater removal of potassium from the soil. Similar synergistic interactions between nitrogen and potassium have been reported in tea by Sharma *et al*. (1977), Bhavanandan and Manipura (1969), Wanyoko (1979), Ranganathan and Natesan (1985), and Sitienei *et al*. (2013). The results demonstrated that treatments T_2 and T_3 consistently recorded lower residual soil nutrient concentrations than the recommended fertilizer treatment, indicating enhanced nutrient uptake by tea plants. Although T_1 maintained higher soil nutrient reserves, the superior nutrient utilization observed in T_2 and T_3 suggests that foliar application of Nano DAP improved fertilizer use efficiency. Furthermore, the performance of T_3, which received only 75% of the recommended basal phosphorus dose, was statistically comparable with T_2, indicating that 25% of the conventional phosphatic fertilizer could be substituted by Nano DAP without adversely affecting nutrient availability and uptake.

Effect of Nano DAP on leaf nutrient concentration

Leaf nitrogen content

The foliar application of Nano DAP significantly influenced leaf nitrogen concentration during all three cropping seasons (Table 5). Treatment T_2 recorded the highest leaf nitrogen content, with values of 4.92%, 3.86% and 4.76%during the early, rainy and back-end seasons, respectively. The nitrogen concentration recorded in T_3 (4.86%, 3.82% and 4.71%) was statistically at par with T_2 throughout the study period. In contrast, the lowest leaf nitrogen content was observed in the recommended fertilizer treatment (T_1), whereas T_5 showed values comparable to T_1.

The improvement in leaf nitrogen concentration under T_2 and T_3 can be attributed to efficient foliar absorption of nitrogen supplied through Nano DAP. The nano-sized particles facilitate rapid penetration through stomata and leaf pores, thereby enhancing nitrogen assimilation and translocation within the plant. Increased nitrogen availability promotes chlorophyll synthesis, amino acid formation and protein metabolism, ultimately improving the nutritional status of tea leaves. Similar improvements in leaf nitrogen concentration following nano fertilizer application have been reported by Chamuah *et al.* (2023) in cabbage and Saikia *et al.* (2024) in tea. Earlier studies by Liu *et al*. (2021) and Hoshina *et al*. (1978) also demonstrated that foliar nitrogen application significantly enhances nitrogen accumulation in tea leaves and improves nutrient use efficiency.

Leaf phosphorus content

Significant differences in leaf phosphorus concentration were observed among the treatments during all three seasons (Table 6). The highest phosphorus content was recorded in T_2, with values of 0.39%, 0.33% and 0.34% during the early, rainy and back-end seasons, respectively. Treatment T_3 remained statistically

Table 4 : Soil available potash (kg/ha) as influenced by application of Nano DAP based fertilizers in July and December, 2024.

Treatments	Soil available K_2O (kg/ha)	
	July, 2024	December, 2024
T_1	237.50	197.13
T_2	226.33	185.56
T_3	228.71	187.70
T_4	229.20	189.21
T_5	234.09	194.59
CD	4.09	5.71
SE(d)	1.87	2.62

Table 5 : Leaf nitrogen content (%) as influenced by application of Nano DAP based fertilizer.

Treatment	Leaf nitrogen content (%)		
	Early season (March-May)	Rainy season (June - September)	Back-end season (October-November)
T_1	4.71	3.54	4.49
T_2	4.92	3.86	4.76
T_3	4.86	3.82	4.71
T_4	4.81	3.75	4.64
T_5	4.74	3.63	4.57
CD	0.09	0.15	0.09
SE(d)	0.04	0.06	0.04

Table 6 : Leaf phosphate content (%) as influenced by application of Nano DAP based fertilizers.

Treatment	Leaf P_2O_5 content (%)		
	Early season (March-May)	Rainy season (June - September)	Back-end season (October-November)
T_1	0.33	0.27	0.28
T_2	0.39	0.33	0.34
T_3	0.38	0.32	0.32
T_4	0.37	0.31	0.31
T_5	0.34	0.28	0.29
CD	0.02	0.02	0.01
SE(d)	0.01	0.01	0.00

comparable with T_2 throughout the experimental period, whereas T_1 recorded the lowest phosphorus concentration. Leaf phosphorus content in T_5 did not differ

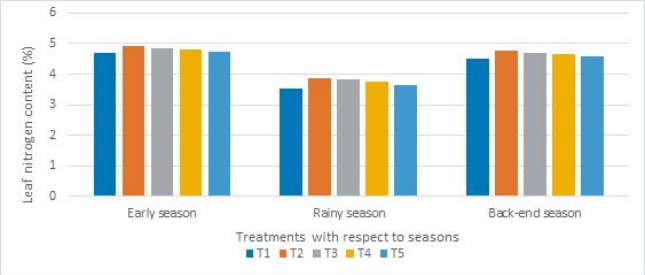

Fig. 4 : Leaf nitrogen bs influenced by application of nano DAP based fertilizer.

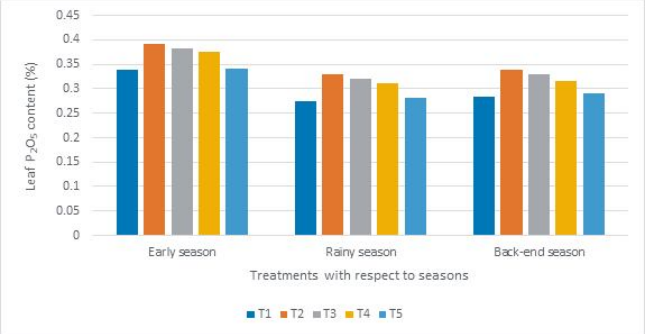

Fig. 5 : Leaf Phosphate content as influenced by application of Nano DAP based fertilizers.

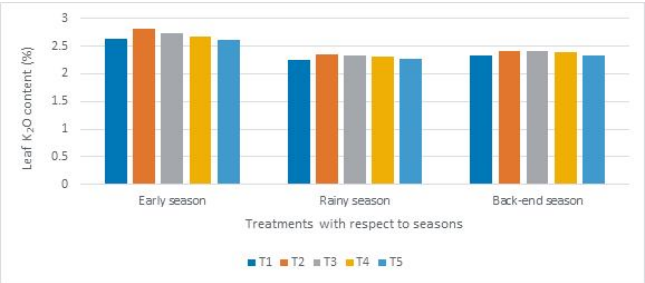

Fig. 6 : Leaf Potash content as influenced by Application of Nano DAP based fertilizers.

significantly from the recommended fertilizer treatment.

The higher phosphorus concentration observed under T_2 and T_3 indicates improved phosphorus uptake and utilization resulting from foliar application of Nano DAP. Since phosphorus is directly involved in ATP synthesis, energy transfer and root growth, its improved availability enhances overall nutrient metabolism. Foliar application also minimizes phosphorus fixation in acidic soils by supplying the nutrient directly to leaf tissues. Similar increases in phosphorus concentration following nano fertilizer application have been reported by Dhansil *et al*. (2018) in pearl millet and Chamuah *et al*. (2023) in cabbage, indicating improved phosphorus use efficiency under nano fertilization.

Leaf potassium content

Leaf potassium concentration was significantly influenced by Nano DAP application during all three seasons (Table 7). Treatment T_2 recorded the highest

Table 7 : Leaf potash content (%) as influenced by application of Nano DAP based fertilizers.

Treatment	Leaf K_2O content (%)		
	Early season (March-May)	Rainy season (June - September)	Back-end season (October-November)
T_1	2.62	2.25	2.33
T_2	2.81	2.34	2.41
T_3	2.74	2.33	2.40
T_4	2.68	2.30	2.38
T_5	2.63	2.26	2.32
CD	0.03	0.042	0.05
SE(d)	0.01	0.01	0.02

potassium content (2.81%, 2.34% and 2.41% during the early, rainy and back-end seasons, respectively), followed by T_3, which remained statistically at par with T_2. The lowest potassium concentration was recorded in T_1, while T_5 produced values comparable to the recommended fertilizer treatment.

Although, Nano DAP supplies only nitrogen and phosphorus, the enhanced potassium concentration observed under T_2 and T_3 may be attributed to the synergistic interaction among essential nutrients. Improved nitrogen and phosphorus nutrition stimulates root activity and enhances potassium absorption, resulting in better nutrient balance within the plant. Potassium is indispensable for enzyme activation, carbohydrate translocation, stomatal regulation and maintenance of cellular osmotic potential, thereby supporting vigorous shoot growth and productivity. Similar improvements in leaf potassium concentration following nano fertilizer application have been reported by Chamuah *et al.* (2023), Dhansil *et al*. (2018) and Saikia *et al*. (2024). Foliar application of Nano DAP markedly improved the concentrations of nitrogen, phosphorus and potassium in tea leaves throughout the cropping period. Treatments T_2 and T_3 consistently produced comparable results, indicating that three foliar sprays of Nano DAP combined with 75% of the recommended basal phosphorus dosewere sufficient to maintain leaf nutrient status comparable with the full recommended phosphorus application. These findings demonstrate that Nano DAP enhances nutrient acquisition and utilization, thereby improving the nutritional status of tea plants.

Effect of Nano DAP on nutrient uptake

Nitrogen uptake

Nitrogen uptake by tea plants differed significantly among treatments during the early, rainy and back-end seasons (Table 8). Treatment T_2 recorded the highest nitrogen uptake (49.70, 55.35 and 67.70 kg ha^{-1}, respectively), followed by T_3 (47.79, 54.10 and 65.20 kg ha^{-1}), which remained statistically at par with T_2. The recommended fertilizer treatment (T_1) recorded the lowest nitrogen uptake throughout the study, whereas T_5 showed values comparable to T_1.

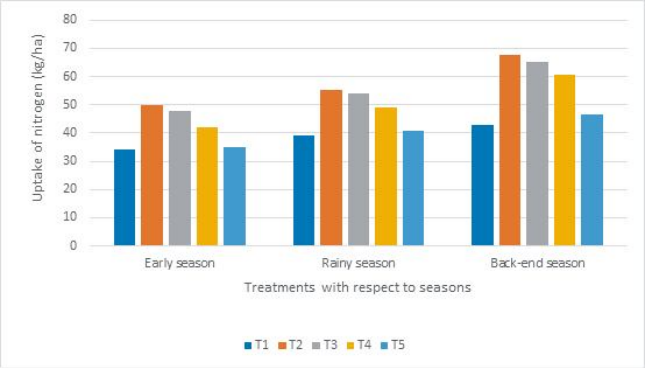

Fig. 7 : Uptake of Nitrogen (Kg/ha) by tea plants as influenced by application of Nano DAP based fertilizer.

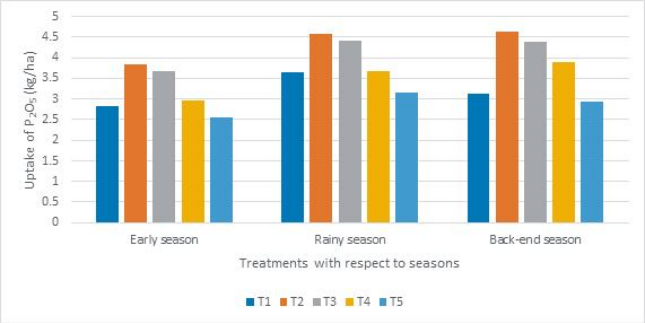

Fig. 8 : Uptake of Phosphate (Kg/ha) by tea plants as influenced by application of Nano DAP based fertilizer.

The increased nitrogen uptake under T_2 and T_3 reflects improved nutrient absorption and utilization resulting from foliar application of Nano DAP. Nano-sized particles increase nutrient availability at the site of metabolism and improve translocation within plant tissues, thereby enhancing fertilizer use efficiency. Similar improvements in nutrient uptake following nano fertilizer application have been reported by Saikia *et al*. (2024) in tea and Dhansil *et al*. (2018) in pearl millet.

Phosphorus uptake

Application of Nano DAP significantly increased phosphorus uptake by tea plants (Table 9). Treatment T_2 recorded the highest phosphorus uptake during all three seasons (3.85, 4.58 and 4.64 kg ha^{-1}), followed closely by T_3 (3.68, 4.42 and 4.38 kg ha^{-1}). Both treatments were statistically comparable and significantly superior to the remaining treatments. The lowest phosphorus uptake was recorded in T_1.

Table 8 : Uptake of nitrogen (kg/ha) by tea plants as influenced by application of Nano DAP based fertilizer.

Treatment	Uptake of nitrogen (kg/ha)		
	Early season (March-May)	Rainy season (June - September)	Back-end season (October-November)
T_1	34.08	39.32	42.79
T_2	49.70	55.35	67.70
T_3	47.79	54.10	65.20
T_4	41.84	48.94	60.57
T_5	35.16	40.76	46.68
CD	2.86	2.51	3.44
SE(d)	1.31	1.15	1.58

Table 9 : Uptake of phosphate (kg/ha) by tea plants as influenced by application of Nano DAP based fertilizer.

Treatment	Uptake of P_2O_5 (kg/ha)		
	Early season (March-May)	Rainy season (June - September)	Back-end season (October-November)
T_1	2.83	3.66	3.14
T_2	3.85	4.58	4.64
T_3	3.68	4.42	4.38
T_4	2.97	3.68	3.89
T_5	2.54	3.16	2.95
CD	0.27	0.35	0.43
SE(d)	0.12	0.16	0.20

Enhanced phosphorus uptake under Nano DAP application can be attributed to direct foliar absorption of phosphorus and reduced losses caused by fixation in acidic tea soils. Improved phosphorus nutrition also enhances energy transfer and metabolic activity, thereby supporting greater nutrient utilization by tea plants. Similar findings have been reported by Dhansil *et al*. (2018) and Chamuah *et al*. (2023).

Potassium uptake

Potassium uptake was significantly influenced by Nano DAP application (Table 10). Treatment T_2 recorded the highest potassium uptake (28.16, 33.57 and 34.23 kg ha^{-1} during the early, rainy and back-end seasons, respectively), while T_3 remained statistically at par with T_2. Treatment T_1 recorded the lowest potassium uptake, whereas T_5 showed values comparable to the recommended fertilizer treatment.

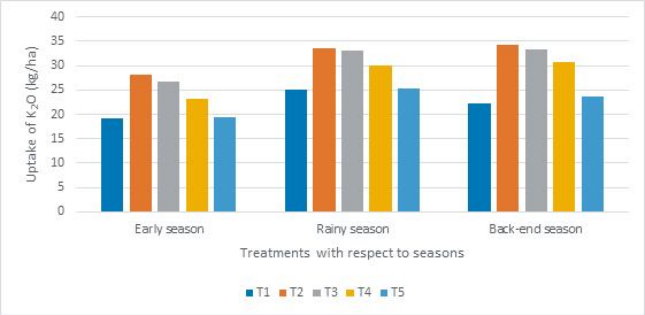

Fig. 9 : Uptake of Potash (Kg/ha) by tea plants as influenced by application of Nano DAP based fertilizer.

Table 10 : Uptake of potash (kg/ha) by tea plants as influenced by application of Nano DAP based fertilizer.

Treatment	Uptake of K_2O (kg/ha)		
	Early season (March-May)	Rainy season (June - September)	Back-end season (October-November)
T_1	19.28	25.01	22.31
T_2	28.16	33.57	34.23
T_3	26.78	33.07	33.28
T_4	23.12	29.98	30.81
T_5	19.49	25.37	23.60
CD	1.70	1.00	1.78
SE(d)	0.55	0.45	0.81

The higher potassium uptake observed under T_2 and T_3 is likely associated with the synergistic effect of nitrogen and phosphorus supplied through Nano DAP, which improved root activity and nutrient transport. Enhanced potassium uptake contributes to efficient carbohydrate translocation, enzyme activation and maintenance of water relations, thereby supporting continuous shoot production in tea. Similar responses have been reported in tea and other crops following nano fertilizer application (Saikia *et al*., 2024; Dhansil *et al*., 2018). Nano DAP significantly enhanced the uptake of nitrogen, phosphorus and potassium compared with the conventional fertilizer treatment. Treatments T_2 and T_3 consistently produced statistically comparable nutrient uptake throughout the experimental period, whereas T_5 failed to maintain uptake comparable with T_2 because of the greater reduction in basal phosphorus application. The results indicate that replacing 25% of the recommended basal phosphorus fertilizer with three foliar sprays of Nano DAP can effectively improve nutrient uptake without compromising plant nutrition. This finding highlights the potential of Nano DAP to enhance fertilizer

use efficiency and support sustainable nutrient management in tea cultivation.

Conclusion

The present investigation demonstrated that foliar application of Nano DAP significantly improved nutrient use efficiency in tea by enhancing leaf nutrient concentration and the uptake of nitrogen, phosphorus and potassium. Among the treatments, T_2 (recommended dose of N, P_2O_5 and K_2O + three foliar sprays of Nano DAP @ 3 mL L^{-1}) recorded the best overall performance. However, T_3 (recommended dose of N and K_2O + 75% of the recommended dose of P_2O_5 + three foliar sprays of Nano DAP @ 3 mL L^{-1}) produced statistically comparable results for soil nutrient status, leaf nutrient concentration and nutrient uptake. This indicates that 25% of the recommended basal phosphorus fertilizer can be substituted by foliar application of Nano DAP without adversely affecting nutrient uptake or plant nutritional status. The findings suggest that Nano DAP can serve as an effective supplementary nutrient source for tea cultivation by improving fertilizer use efficiency while reducing the requirement for conventional phosphatic fertilizers. Adoption of this nutrient management strategy may lower fertilizer input, minimize phosphorus fixation in acidic tea soils, and contribute to more economical and environmentally sustainable tea production. Further long-term and multi-location studies are recommended to validate the performance of Nano DAP under different tea-growing environments and management conditions.

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