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Response of potato (*Solanum tuberosum*) to nano-DAP based nutrient management under varying phosphorus levels at sub-tropics of North-Western Indian region

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Background: Low phosphorus (P) use efficiency due to fixation limits potato productivity; therefore, this study evaluated the potential of nano-diammonium phosphate (nano-DAP) to sustain productivity under reduced P inputs.

Methods: A two-year field experiment (2024–25 and 2025–2026) was conducted at Lovely Professional University, Jalandhar, Punjab, India, under randomized complete block design to compare graded levels of conventional P with and without nano-DAP (seed treatment and foliar application). Agronomic parameters, productivity, nutrient uptake, and stress tolerance parameters were assessed, along with multivariate and FTIR analyses.

Results: The treatment T₁₁ (75% P through DAP + seed dressing of nano-DAP @ 10 mL L⁻¹ water + two foliar sprays of nano-DAP @ 0.4% at 35 and 55 DAS + 100% recommended N and K) produced significantly higher growth and yield attributes, resulting in substantially higher tuber yield (289.47 q ha⁻¹) and biological yield (385.71 q ha⁻¹) over other treatments, and remained statistically at par with T₆ (100% P through DAP + 100% recommended N and K) and T₁₂ (100% P through DAP + seed dressing of nano-DAP @ 10 mL L⁻¹ water + one foliar spray of nano-DAP @ 0.4% at 35 DAS + 100% recommended N and K).

Conclusion: Strategic integration of nano-diammonium phosphate (nano-DAP), i.e., seed dressing @ 10 mL L⁻¹ + two foliar sprays @ 0.4% at 35 and 55 DAS) with 75% P through DAP improved P use efficiency (agronomic and apparent recovery efficiency) and enabled a 25% reduction in conventional P without yield loss in potato production.

KEYWORDS

Indo-Gangetic plains, nano-diammonium phosphate, nutrient management, nutrient use efficiency, resource optimization

1 Introduction

Phosphorus (P) is an essential macronutrient regulating plant growth, metabolism, and productivity (Heuer et al., 2017; Kafle et al., 2019). It plays a key role in energy transfer, nucleic acid synthesis, membrane stability, and enzymatic regulation, thereby influencing photosynthesis, respiration, and carbohydrate metabolism (Kafle et al., 2019). Adequate P availability is critical for root development, early establishment, and reproductive growth (Reddy et al., 2025). However, phosphorus is one of the least efficiently utilized nutrients in cropping systems (Hasan et al., 2016), with only 10–20% of applied P taken up in the first season, while the remainder becomes unavailable due to fixation or precipitation with Fe, Al, and Ca compounds (Hasan et al., 2016; Hasbullah et al., 2020; Li et al., 2024). Similarly, crop recovery of applied P rarely exceeds 10–25% in the first year, with residual P accumulating in soil for later use (Roberts and Johnston, 2015). This imbalance between high fertilizer input and low crop availability, often termed the “phosphorus paradox”, leads to excessive fertilizer application, increased production costs, and depletion of finite phosphate reserves (Hasan et al., 2016; Ibrahim et al., 2022). The low phosphorus use efficiency is primarily governed by soil chemical reactions that convert soluble phosphate into sparingly soluble forms, thereby limiting its mobility and bioavailability (Kafle et al., 2019; Hedley and McLaughlin, 2008). Consequently, a substantial portion of applied P becomes immobilized in soil pools or adsorbed onto soil constituents (López-Arredondo et al., 2014). Low phosphorus use efficiency is mechanistically driven by rapid adsorption of phosphate ions onto Fe/Al oxides in acidic soils and precipitation as Ca–P minerals in alkaline soils (Subramani and Balakrishnan, 2026), which reduces diffusion, root interception, and plant availability.

Potato (*Solanum tuberosum* L.) is a major global food crop and an important contributor to food security (Alva et al., 2011). In the subtropical agroecosystems of north-western India, it is an important *rabi* crop with high yield potential, significantly contributing to farm profitability, crop diversification, and the regional agri-economy. In India, it was cultivated on 2.33 million ha with a production of 60.14 million tonnes during 2022–23 (GoI, 2024). Owing to its high nutrient demand and rapid biomass accumulation, potato is highly responsive to phosphorus fertilization (Hopkins et al., 2008; Al-Uthery and Al-Shami, 2019). Phosphorus plays an important role in root growth, stolon development, tuber initiation, and energy transfer processes essential for carbohydrate metabolism and tuber bulking (Samal et al., 2025). However, the shallow root system of potato restricts soil exploration, making the crop highly dependent on readily available phosphorus during early growth stages; consequently, inadequate supply can delay tuberization and reduce yield and quality (Hopkins et al., 2008), rendering potato an ideal model for evaluating phosphorus-efficient technologies. Although conventional phosphatic fertilizers such as diammonium phosphate (DAP) are widely used, phosphorus use efficiency remains low, with crops recovering only about 18–20% of applied P, while the remainder is immobilized through fixation, precipitation, and microbial processes (Roberts and Johnston, 2015; Jakhar et al., 2022; Tiwari et al., 2022; Reddy et al., 2025).

Recent advances in nutrient management have introduced nanotechnology as a promising approach to enhance fertilizer use efficiency (Guo et al., 2018; Al-Mamun et al., 2021). Nano-fertilizers are engineered at the nanoscale, and their small particle size with high surface-area-to-volume ratio improves reactivity, solubility, and interactions with plant tissues (Sheershwil et al., 2025). These properties enable controlled nutrient release, targeted delivery, and better synchronization between nutrient supply and crop demand (Singh et al., 2024a; Kekeli et al., 2025). Consequently, nano-fertilizers are increasingly recognized for improving nutrient use efficiency, reducing losses, and promoting sustainable crop production (Saurabh et al., 2024; Raliya et al., 2017; Al-Mamun et al., 2021). Nano-phosphorus fertilizers enhance nutrient availability and uptake through controlled release and improved absorption compared with conventional sources (Subramani and Balakrishnan, 2026). Field studies report yield increases of 14.7–34.8% in wheat following nano-phosphorus application (Reddy et al., 2025), largely due to enhanced photosynthetic efficiency, enzymatic activity, and nutrient translocation (Sweety et al., 2024; Keerthana et al., 2024). Nano-diammonium phosphate (nano-DAP) further represents an advancement by supplying both nitrogen and phosphorus in nano-form for efficient plant utilization (Karn et al., 2025). Its dual mode of application (foliar and soil) facilitates rapid nutrient absorption while reducing soil fixation losses (Reddy et al., 2025). In addition, nano-DAP has been reported to improve physiological performance by enhancing chlorophyll synthesis and metabolic activities associated with protein synthesis (Keerthana et al., 2024; Reddy et al., 2025), while also offering the potential to reduce fertilizer input costs and environmental pollution (Kumar et al., 2021; Kekeli et al., 2025).

Despite the widespread use of phosphatic fertilizers, phosphorus use efficiency remains low due to rapid soil fixation and limited availability during early growth stages, and the field-level integration of nano-DAP with conventional DAP in potato under subtropical conditions remains insufficiently explored. Moreover, linking agronomic performance with biochemical responses is essential; hence, Fourier Transform Infrared (FTIR) spectroscopy was employed to characterize phosphorus-associated functional groups. It is hypothesized that the balanced integration of nano-DAP and conventional DAP can sustain productivity while reducing fertilizer inputs. Accordingly, the present study aimed to evaluate their combined effects on growth, yield attributes, and yield of potato, assess nutrient uptake, physiological traits and stress tolerance, and characterize phosphorus-related functional groups using FTIR spectroscopy.

2 Materials and methods

2.1 Study area

A field experiment was conducted during two consecutive *rabi* seasons (2024–25 and 2025–26) at the Agricultural Research Farm of Lovely Professional University, Phagwara, Jalandhar, Punjab, India (31°13'26.4" N, 75°46'14.9" E), situated at an elevation of 234 m above

mean sea level (Figure 1). The experimental site lies in the north-western Indo-Gangetic Plains and is characterized by a semi-arid, subtropical climate with distinct seasonal variations. Summers (April to June) are typically hot and dry, with maximum temperatures ranging from 42 to 48 °C. The southwest monsoon (July to September) contributes the majority of the annual rainfall, with total precipitation ranging between 500 and 800 mm, accompanied by warm and humid conditions. The post-monsoon period (October–November) is generally mild, followed by cool winters (December to February), during which minimum temperatures range from 4 to 8 °C. Seasonal transitions are often marked by occasional rainfall events and fluctuations in temperature. The experimental soil was classified as sandy loam based on particle size analysis using the hydrometer method described by Piper (1966). Soil pH (7.75) and electrical conductivity (0.177 dS m^{-1}) were determined in a 1:2 soil-water suspension using digital pH and conductivity meters following the procedure outlined by

Jackson (1973). Based on the observed EC value, the soil was classified as non-saline ($\text{EC} < 1 \text{ dS m}^{-1}$), as per standard salinity classification (Richards, 1954). Soil organic carbon content was 0.42%, estimated using the Walkley and Black wet oxidation method (Walkley and Black, 1934). The soil fertility status showed medium levels of available macronutrients, as the available phosphorus and potassium were 5.75 and $212.50 \text{ kg ha}^{-1}$, respectively. Phosphorus was determined using the sodium bicarbonate extraction method (Olsen et al., 1954), while potassium was estimated through neutral ammonium acetate extraction (Jackson, 1973). Micronutrient concentrations (Zn, Fe, Cu and Mn) were extracted using the DTPA-TEA method and quantified through atomic absorption spectrophotometry following Lindsay and Norvell (1978), with values of 14.45, 15.95, 1.28 and 14.53 mg kg^{-1} , respectively. The soil exhibited a bulk density of 1.47 g cm^{-3} , which was determined using a core method (core soil sampler) as described by Blake and Hartge (1986).

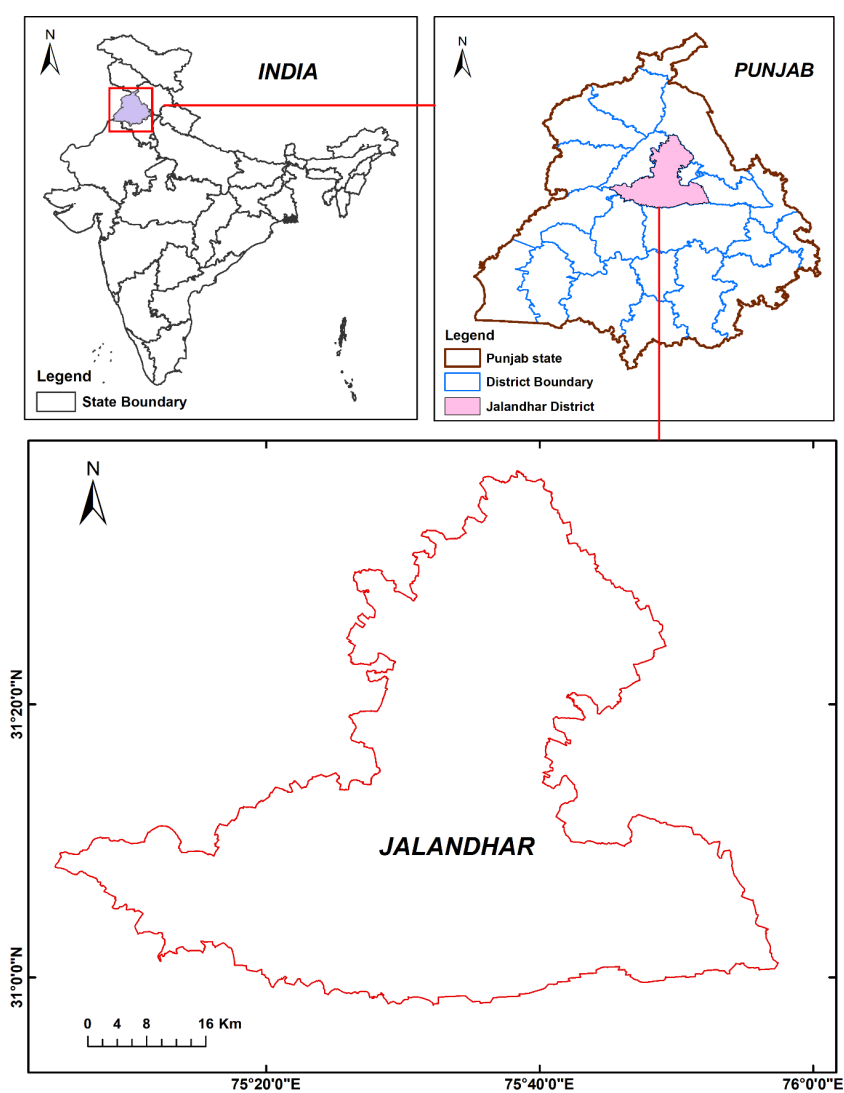


FIGURE 1
Study area (Jalandhar, Punjab, India).

2.2 Experimental design and crop management practices

The study was conducted in a randomized complete block design with three replications during the rabi seasons of 2024–25 and 2025–26, comprising twelve nutrient management treatments involving graded levels of phosphorus through diammonium phosphate (DAP) in combination with recommended doses of nitrogen and potassium, along with strategic integrated use of nano-DAP. The treatments were designed to evaluate the potential for partial substitution of conventional phosphorus fertilisers with nano-DAP. Nano-DAP was incorporated as a supplementary nutrient source through seed treatment @ 10 mL L⁻¹ water before planting and foliar application @ 0.4% concentration at 35 days after sowing, with a second spray at 55 days after sowing in selected treatments. Nano-diammonium phosphate used in the study was procured from the Indian Farmers Fertiliser Cooperative Limited (IFFCO), India. The product was in liquid formulation containing 8.0% nitrogen (w/v) and 16.0% phosphorus pentoxide (P₂O₅, w/v), with nanoparticle size below 100 nm. Potato seed tubers were treated with nano-diammonium phosphate (nano-DAP) as per the treatment combinations before planting. For seed treatment, tubers were sprayed with a nano-DAP solution (10 mL L⁻¹ water), shade-dried, and planted immediately in the respective plots. Foliar application of nano-DAP (0.4%) was carried out as per treatment schedule. Each experimental plot measured 5.0 m × 6.0 m. Standard agronomic practices recommended for potato cultivation in the region were followed throughout the crop growth period. Farmyard manure (FYM) was incorporated at 50 t ha⁻¹ before planting along with the recommended dose of fertilizers (RDF) of 187:62:62 kg ha⁻¹ of N, P₂O₅ and K₂O, respectively, as recommended in the Package of Practices for Cultivation of Vegetables (PAU, 2021). Nitrogen, phosphorus and potassium were supplied through urea, diammonium phosphate and muriate of potash, respectively. The entire quantities of phosphorus and potassium and half of the nitrogen were applied as basal at planting, whereas the remaining nitrogen was applied in split doses as top-dressing according to the recommended schedule. Nitrogen supplied through DAP was accounted for, and the remaining nitrogen was adjusted through urea to maintain a uniform recommended dose under different treatments. The potato cultivar Kufri Pukhraj, an early maturing and widely adapted variety suitable for the north-western Indo-Gangetic plains, was planted during the rabi season at a spacing of 60 cm × 20 cm using seed tubers at a seed rate of 45 q ha⁻¹. Weed management involved a pre-emergence application of metribuzin (Sencor 70 WP) at 0.5 kg ha⁻¹, followed by a post-emergence spray of paraquat (Gramoxone 24 SL) at 1.25 L ha⁻¹ when 5–10% crop emergence was observed. Irrigation was provided in accordance with crop water requirements and prevailing rainfall conditions, with four irrigations applied after planting in each season as per the crop requirement. To manage late blight incidence, two prophylactic foliar sprays of Ridomil Gold (8% metalaxyl + 64% mancozeb) at 700 g ha⁻¹ were applied during the crop growth period following standard plant protection practices.

2.3 Measurements of growth, yield, physiological traits and nutrient uptake

Growth parameters, yield attributes, productivity, and nutrient uptake of potato were recorded. To avoid border effects, two outer rows on each side were excluded, and observations and yield were taken from the central rows. Yield was calculated on a net plot basis and converted to hectare yield. Growth parameters included plant height, leaf area index (LAI), tuber dry matter accumulation and haulm dry matter accumulation at harvest. Yield attributes comprised number of stems per plant, tubers per plant, tuber weight per plant and mean tuber weight, while total productivity was assessed in terms of tuber yield, haulm yield and biological yield. Plant height was measured from five randomly selected plants in each net plot using a measuring scale and expressed in centimeters. Leaf area index was determined using a SunScan canopy analyzer. For estimation of dry matter accumulation, two representative plants were sampled from each net plot and oven-dried at 65 ± 5 °C until constant weight, after which dry biomass was expressed on an area basis. Yield attributes were determined by recording the number of stems per plant, tubers per plant, tuber weight per plant and average tuber weight. Observations on stems and tubers were recorded from two randomly selected plants in each net plot and averaged. The number of plants selected for observations (growth and yield attributes) followed standard agronomic practices, ensuring adequate representation while minimizing plot disturbance. Tuber weight per plant was recorded at haulm cutting using an electronic balance, while average tuber weight was calculated by dividing total tuber weight by the number of tubers per plant. Tuber and haulm yields were determined from the net plot harvest and expressed on a hectare basis. Harvest index (HI) was calculated as the ratio of tuber yield to biological yield (tuber + haulm yield) and expressed as percentage. Plant samples were oven-dried and finely ground prior to analysis. Nitrogen content was determined using the modified Kjeldahl digestion method following Piper (1966), where samples were digested with concentrated H₂SO₄ on a digestion block at 360–380 °C until a clear digest was obtained. For phosphorus and potassium estimation, plant samples were digested with a tri-acid mixture (HNO₃:HClO₄:H₂SO₄, 9:3:1) at 180–200 °C until a clear solution was obtained. Phosphorus was determined by the vanadomolybdate yellow colour method, while potassium was estimated from the same digest using flame photometry following Jackson (1973). Total nutrient uptake was calculated by multiplying nutrient concentration by the respective dry matter yield of tuber and haulm. Physiological parameters, *viz.*, relative water content (RWC), membrane stability index (MSI), membrane injury index (MII), chlorophyll content, and SPAD readings, were evaluated to assess plant functional status. Fresh leaf samples were collected and promptly transferred to the laboratory to prevent moisture loss. Initial fresh weight (FW) was recorded, after which leaves were floated in distilled water for 4 hours to achieve full turgidity. The samples were then gently blotted and weighed to obtain turgid weight (TW). Subsequently, samples were oven-dried at 50 °C for 24 hours to determine dry weight (DW). Relative water content was

computed using the standard formula (Barrs and Weatherley, 1962).

$$\text{RWC}(\%) = [(\text{FW} - \text{DW}) / (\text{TW} - \text{DW})] \times 100$$

Membrane stability and injury were assessed through electrolyte leakage analysis using fully expanded upper canopy leaves of potato plants to ensure uniform physiological status. Approximately 200 mg of fresh leaf tissue was immersed in 10 mL of double-distilled water. One set of samples was incubated at 40 °C for 30 min and electrical conductivity was recorded (C_1), while another set was boiled at 100 °C for 10 min to obtain total conductivity (C_2). Membrane stability index was calculated as $\text{MSI}(\%) = [1 - (C_1 / C_2)] \times 100$, whereas membrane injury index was expressed as $\text{MII}(\%) = (C_1 / C_2) \times 100$ following the method of Blum and Ebercon (1981) and Dionisio-Sese and Tobita (1998). Chlorophyll concentration was determined using the acetone extraction method followed by spectrophotometric measurement at 645 and 663 nm according to the method of Arnon (1949). In addition, leaf greenness was measured non-destructively using a SPAD chlorophyll meter by taking readings from fully expanded upper leaves, and the average value was recorded (Markwell et al., 1995).

2.4 Calculation of nutrient use efficiency indices

Nutrient use efficiency (NUE) was evaluated using standard agronomic indices widely used in fertilizer response studies, with specific reference to phosphorus in the present investigation. The indices were computed from tuber yield and phosphorus uptake data, following the procedures described by Dobermann (2007) and Ladha et al. (2005). These indices provide complementary insights into crop response to applied nutrients, fertilizer productivity, and nutrient recovery efficiency (Cassman et al., 2002; Fixen et al., 2015). In the present study, these indices were particularly useful for assessing the effectiveness of nano-DAP in enhancing phosphorus availability, uptake, and utilization efficiency compared with conventional fertilization.

Agronomic efficiency (AE): Agronomic efficiency represents the increase in tuber yield per unit of applied nutrient (phosphorus).

$$\text{AE} = \frac{Y_p - Y_0}{P_a}$$

Where, Y_p = tuber yield in nutrient-treated plots (q ha^{-1}), Y_0 = tuber yield in control plots (q ha^{-1}), P_a = amount of phosphorus applied ($\text{kg P}_2\text{O}_5 \text{ ha}^{-1}$).

Apparent recovery efficiency (RE): Recovery efficiency indicates the proportion of applied nutrient (phosphorus) taken up by the crop.

$$\text{RE}(\%) = \frac{U_p - U_0}{P_a} \times 100$$

Where, U_p = total phosphorus uptake in treated plots (kg ha^{-1}), U_0 = total phosphorus uptake in control plots (kg ha^{-1}), P_a = phosphorus applied ($\text{kg P}_2\text{O}_5 \text{ ha}^{-1}$).

2.5 Fourier transform infrared spectroscopy

Functional groups of the samples were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) following Caldera-Villalobos et al. (2019). Spectra were recorded using an ATR-FTIR spectrometer (Spectrum Two, PerkinElmer, USA) equipped with a diamond crystal. For FTIR analysis, representative treatments (T1, T2, T5, T8, T10, and T11) were selected to capture the variability among control, conventional fertilization, and nano-DAP-integrated nutrient management practices. For sample preparation, finely powdered material (10 mg) was mixed with potassium bromide (100 mg) to obtain a homogeneous mixture and placed on the sample holder. Spectral measurements were recorded in transmittance mode using Spectrum 10 software, with air as the background. The spectra were acquired over the wavenumber range of $4000\text{--}400 \text{ cm}^{-1}$ at a resolution of 4 cm^{-1} .

2.6 Data analysis

The experimental data were subjected to analysis of variance (ANOVA) to evaluate the effects of different treatments on potato growth, yield attributes, productivity, and nutrient uptake under randomized block design. Before analysis, data were tested for normality and homogeneity of variance to ensure compliance with ANOVA assumptions. Before pooling, the homogeneity of data across years was assessed by testing the significance of year effects and treatment $\times$ year interaction. As these effects were non-significant, indicating consistent treatment responses across the two cropping seasons (2024–25 and 2025–26), the data were pooled and analysed using combined ANOVA, considering treatments as fixed effects and years as a random factor. Treatment means were compared using the least significant difference (LSD) test at the 5% level of significance ($p \leq 0.05$). All ANOVA computations were performed using IBM SPSS Statistics (version 20.0, SPSS Inc., Chicago, USA). Pearson's correlation analysis and principal component analysis (PCA) were conducted using OriginPro (version 10.1, OriginLab Corporation, USA) to examine relationships among agronomic parameters and yield.

3 Results

3.1 Agronomic parameters

3.1.1 Growth characteristics

The growth parameters, viz., plant height, leaf area index (LAI), haulm dry matter accumulation (DMA), and tuber DMA of potato were significantly influenced by phosphorus fertilization strategies (Table 1). A consistent and progressive enhancement in these parameters was observed with increasing phosphorus levels and the integration of nano-DAP. Significantly higher plant height (49.88 cm) was recorded under T_{11} (75% P through DAP + seed dressing with nano-DAP @ 10 mL L^{-1} + foliar spray @ 0.4% at 35

TABLE 1 Treatment description.

Treatment	Treatment details
T1	N ₀ P ₀ K ₀ (absolute control)
T2	100% recommended N and K
T3	25% P through DAP + 100% recommended N and K
T4	50% P through DAP + 100% recommended N and K
T5	75% P through DAP + 100% recommended N and K
T6	100% P through DAP + 100% recommended N and K
T7	25% P through DAP + seed dressing of nano-DAP @ 10 mL L ⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + second spray @ 0.4% at 55 DAS + 100% recommended N and K
T8	50% P through DAP + seed dressing of nano-DAP @ 10 mL L ⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + 100% recommended N and K
T9	50% P through DAP + seed dressing of nano-DAP @ 10 mL L ⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + second spray @ 0.4% at 55 DAS + 100% recommended N and K
T10	75% P through DAP + seed dressing of nano-DAP @ 10 mL L ⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + 100% recommended N and K
T11	75% P through DAP + seed dressing of nano-DAP @ 10 mL L ⁻¹ water + foliar spray of nano DAP @ 0.4% at 35 DAS + second spray @ 0.4% at 55 DAS + 100% recommended N and K
T12	100% P through DAP + seed dressing of nano-DAP @ 10 mL L ⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + 100% recommended N and K

and 55 DAS + 100% recommended N and K), which was statistically at par with T_{1 2} (100% P through DAP + nano-DAP seed dressing + foliar spray @ 35 DAS + 100% recommended N and K; 51.07 cm) and T₆ (100% P through DAP + 100% recommended N and K; 48.90 cm). The plant height under T_{1 1} was approximately 1.99–2.08 times higher than the absolute control (T₁ : N₀P₀K₀). A similar trend was observed for LAI, where T_{1 1} (2.60) remained statistically comparable with T_{1 2} (2.70) and T₆ (2.55), while significantly outperforming the remaining treatments. Furthermore, the highest haulm DMA (234.76 g m⁻²) and tuber DMA (366.49 g m⁻²) were recorded under T_{1 1}, which were at par with T_{1 2} (239.13 and 372.76 g m⁻², respectively) and T₆ (228.84 and 355.08 g m⁻², respectively). The haulm DMA under T_{1 1} was approximately 2.25–2.35 times higher, while tuber DMA was about 2.49–2.62 times higher than the control (T₁). However, the differences among T₆, T_{1 1}, and T_{1 2} were marginal, indicating that comparable growth responses can be achieved either through full conventional phosphorus application or through partial substitution integrated with nano-DAP, likely due to improved phosphorus availability and utilization efficiency.

3.1.2 Yield parameters

The yield attributes of potato, viz., number of stems plant⁻¹, tubers plant⁻¹, and tuber weight plant⁻¹, were significantly influenced by phosphorus fertilization treatments (Table 2). Significantly higher number of stems (3.96 plant⁻¹), tubers (10.59 plant⁻¹), and tuber weight (448.10 g plant⁻¹) were recorded under T_{1 1} [75% P through DAP + seed dressing of nano-DAP @ 10 mL L⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + second spray @ 0.4% at 55 DAS + 100% recommended N and K]. These values were statistically at par with T_{1 2} [100% P through DAP + seed dressing of nano-DAP @ 10 mL L⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + 100% recommended N and K] and T₆ [100% P through DAP + 100% recommended N and K], while remaining significantly higher than the other treatments. However, average

tuber weight did not differ significantly among treatments. The comparatively lower yield attributes observed under reduced phosphorus levels indicate that an adequate supply of phosphorus is critical for optimal yield formation.

3.1.3 Yield

Significant variation in tuber, haulm, and biological yields of potato was observed under different phosphorus fertilization treatments (Table 2). Among the treatments, T_{1 1} (75% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 and 55 DAS + 100% recommended N and K) recorded significantly higher tuber, haulm, and biological yields (289.47, 96.24, and 385.71 q ha⁻¹, respectively), which were 108.04%, 155.77%, and 118.20% higher than the absolute control (T₁), respectively. However, T_{1 1} remained statistically at par with T_{1 2} (100% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 DAS + 100% recommended N and K), which recorded the highest tuber (299.84 q ha⁻¹), haulm (98.72 q ha⁻¹), and biological yields (398.56 q ha⁻¹), and T₆ (100% recommended P through DAP + 100% recommended N and K), which recorded tuber, haulm, and biological yields of 284.00, 94.00, and 377.30 q ha⁻¹, respectively. Treatments receiving lower phosphorus levels produced comparatively lower yields, indicating constrained productivity under inadequate phosphorus supply. The balanced integration of conventional phosphorus with nano-DAP sustained higher yields, demonstrating improved phosphorus availability and use efficiency even at reduced fertilizer levels. However, the harvest index of potato did not differ significantly among different phosphorous fertilization.

3.2 Association between agronomic parameters and productivity

The correlation analysis (Figure 2) revealed strong positive associations among growth traits, yield attributes, and tuber yield,

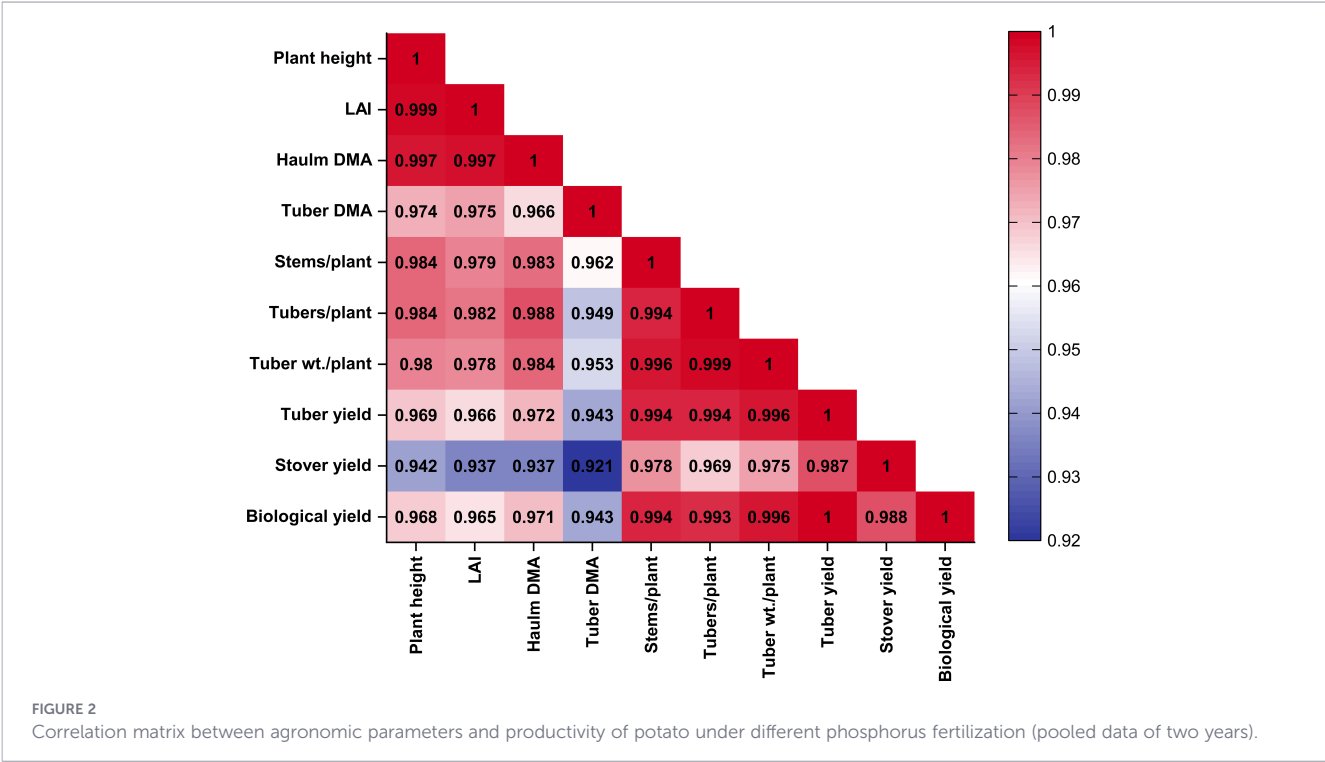
TABLE 2 Effect of different phosphorus fertilization on growth parameters, yield attributes and yield of potato (pooled data of two years).

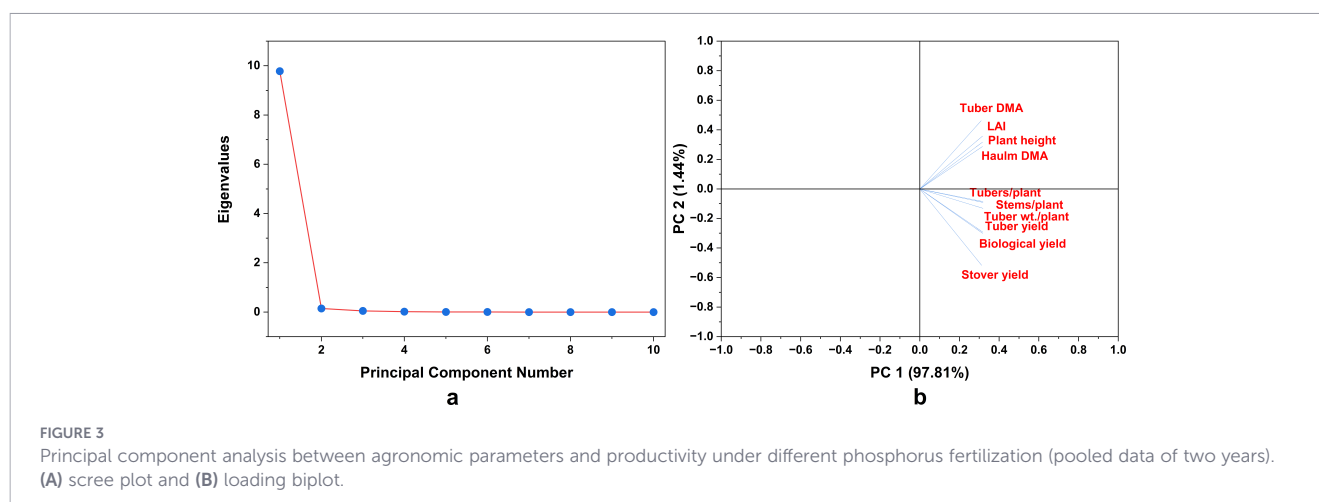
Treatments	Growth parameters					Yield attributes				Yield		Harvest index (%)
	Plant height (cm)	LAI	Haulm DMA (g m ⁻²)	Tuber DMA (g m ⁻²)	Stems/plants	Tubers plant ⁻¹	Tuber wt. plant ⁻¹ (g)	Average tuber weight (g)	Tuber (q ha ⁻¹)	Haulm (q ha ⁻¹)	Biological (q ha ⁻¹)	
T1	24.60	1.54	101.62	142.34	1.52	6.39	262.19	41.03	139.14	37.63	176.77	77.24
T2	31.54	1.85	137.90	190.86	2.07	7.48	313.64	41.93	178.96	51.42	230.38	77.68
T3	35.75	1.85	160.44	229.62	2.50	8.18	338.72	41.41	201.00	59.44	260.44	77.18
T4	40.00	2.06	182.39	270.19	2.97	8.87	373.45	42.10	231.42	71.68	303.10	76.35
T5	44.69	2.31	204.17	311.04	3.41	9.53	407.56	42.77	256.58	81.37	337.95	75.92
T6	48.90	2.55	228.84	355.08	3.85	10.25	440.25	42.95	284.00	94.00	377.30	75.13
T7	39.88	2.00	184.21	271.68	3.00	8.89	376.82	42.39	215.00	68.94	283.94	75.72
T8	39.95	2.04	186.00	273.84	3.02	8.93	379.32	42.48	236.87	74.02	310.89	76.19
T9	44.63	2.27	207.15	313.86	3.42	9.59	409.66	42.72	252.09	82.36	334.45	75.37
T10	44.75	2.34	210.06	315.00	3.44	9.64	414.00	42.95	262.23	87.00	349.23	75.09
T11	49.88	2.60	234.76	366.49	3.96	10.59	448.10	42.31	289.47	96.24	385.71	75.05
T12	51.07	2.70	239.13	372.76	4.12	10.74	456.85	42.54	299.84	98.72	398.56	75.23
SEm (±)	1.38	0.06	5.70	12.22	0.14	0.20	8.16	–	5.70	2.30	7.80	–
LSD (p=0.05)	4.12	0.19	17.05	36.65	0.40	0.58	24.45	NS	17.05	6.93	23.40	NS

indicating that improved vegetative development promoted better yield formation in potato. Growth parameters, including plant height, leaf area index (LAI), haulm dry matter accumulation (DMA), and tuber DMA, were positively correlated with yield attributes such as stems plant⁻¹, tubers plant⁻¹, and tuber weight plant⁻¹, with correlation coefficients ranging from $r = 0.949$ to 0.988 . Among these, haulm DMA showed strong associations with stems plant⁻¹ ($r = 0.983$), tubers plant⁻¹ ($r = 0.988$), and tuber weight plant⁻¹ ($r = 0.984$), while tuber DMA was strongly correlated

with stems plant⁻¹ ($r = 0.962$), tubers plant⁻¹ ($r = 0.949$), and tuber weight plant⁻¹ ($r = 0.953$), reflecting efficient biomass production and assimilate partitioning. Furthermore, yield attributes exhibited strong positive correlations with tuber yield, where stems plant⁻¹ ($r = 0.994$), tubers plant⁻¹ ($r = 0.994$), and tuber weight plant⁻¹ ($r = 0.996$) contributed substantially to enhanced productivity.

Principal component analysis (Figure 3) further supported these relationships, with PC1 explaining 97.81% of the total variance, indicating that trait variability was predominantly





governed by overall crop growth and productivity. All variables showed strong positive loadings on PC1. In contrast, PC2 accounted for only 1.44% of the variance, indicating negligible residual variation. The scree plot confirmed the dominance of PC1, suggesting that a single component adequately explains the dataset. The results highlight strong integration among growth, yield attributes, and productivity under different phosphorus management practices.

3.3 Nutrient uptakes

The uptake of nitrogen (N), phosphorus (P), and potassium (K) by potato was significantly influenced by different phosphorus fertilization treatments (Table 3). Total nutrient uptake increased progressively with increasing phosphorus levels. The highest total uptake of N, P, and K was recorded under T_{12} (100% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 DAS + 100% recommended N and K) (119.70, 26.10, and 180.60 kg ha⁻¹, respectively), which was statistically at par with T_{11} (75% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 and 55 DAS + 100% recommended N and K) (117.66, 25.21, and 171.86 kg ha⁻¹, respectively) and T_6 (100% recommended P through DAP + 100% recommended N and K) (110.27, 24.46, and 169.46 kg ha⁻¹, respectively). These treatments also exhibited higher nutrient accumulation in both haulm and tuber components, indicating efficient nutrient partitioning. In contrast, the lowest nutrient uptake was observed under T_1 (absolute control, $N_0P_0K_0$) (47.73, 10.46, and 71.13 kg ha⁻¹ for N, P, and K, respectively), highlighting the limiting effect of inadequate phosphorus supply.

3.4 Nutrient use efficiencies

Nutrient use efficiency indices were significantly influenced by different phosphorus management treatments (Figure 4). Agronomic efficiency (AE) and apparent recovery efficiency (RE) improved with the integration of nano-DAP along with conventional fertilization. Among the treatments, T_{11} (75% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar

spray @ 0.4% at 35 and 55 DAS + 100% recommended N and K) recorded the highest AE (2.38 q kg⁻¹ P₂O₅) and RE (24.99%) as compared to the other treatments. Although T_{12} (100% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 DAS + 100% recommended N and K) recorded a higher numerical value of tuber yield, its AE (1.95 q kg⁻¹ P₂O₅) and RE (20.18%) were lower than T_{11} .

3.5 Physiological and stress tolerance parameters

Physiological and stress tolerance parameters of potato were significantly influenced by phosphorus fertilization treatments (Table 4). SPAD values ranged from 38.7 under T_1 (absolute control, $N_0P_0K_0$) to 53.3 under T_{11} (75% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 and 55 DAS + 100% recommended N and K), which remained statistically at par with T_{12} (100% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 DAS + 100% recommended N and K) and T_6 (100% recommended P through DAP + 100% recommended N and K). Chlorophyll content varied from 1.60 to 2.73 mg g⁻¹, with the maximum value recorded under T_{12} , remaining statistically at par with T_{11} and T_6 . The membrane stability index ranged from 57.3% to 79.7%, with higher values observed under T_{11} , T_{12} , and T_6 . In contrast, the membrane injury index ranged from 20.0% to 42.7% and exhibited an inverse trend, with lower values under these treatments, with no significant differences among them. Relative water content varied from 68.0% to 91.0%, with higher values recorded under T_6 and T_{12} , followed by T_{11} ; however, these treatments remained statistically comparable.

3.6 Fourier transform infrared spectroscopy

The FTIR spectra (Figure 5) of potato samples under different fertilization treatments showed characteristic absorption bands between 4000 and 400 cm⁻¹, associated with major organic and phosphorus-related functional groups. All treatments exhibited a broad band near 3274–3281 cm⁻¹, indicating O–H stretching

TABLE 3 Effect of different phosphorus fertilization on nutrient uptakes (nitrogen, phosphorus and potassium) of potato (pooled data of two years).

Treatments	Nitrogen (kg ha ⁻¹)			Phosphorus (kg ha ⁻¹)			Potassium (kg ha ⁻¹)		
	Haulm	Tuber	Total	Haulm	Tuber	Total	Haulm	Tuber	Total
T1	19.10	28.63	47.73	3.12	7.34	10.46	19.85	51.28	71.13
T2	23.76	37.95	61.71	4.38	9.21	13.59	28.01	64.91	92.92
T3	30.21	46.28	76.49	4.75	11.26	16.01	32.12	82.14	114.26
T4	31.56	53.88	85.44	5.63	13.22	18.85	35.45	92.87	128.32
T5	38.42	62.45	100.87	6.01	15.98	21.99	39.78	111.26	151.04
T6	39.51	70.76	110.27	7.02	17.44	24.46	44.52	124.94	169.46
T7	35.20	56.40	91.60	5.20	12.08	17.28	37.20	98.40	135.60
T8	34.10	57.20	91.30	5.60	13.80	19.40	36.80	96.20	133.00
T9	38.90	63.11	102.01	6.14	15.02	21.16	41.25	107.96	149.21
T10	39.20	64.50	103.70	6.40	16.00	22.40	42.10	112.30	154.40
T11	43.98	73.68	117.66	7.18	18.03	25.21	45.90	125.96	171.86
T12	44.50	75.20	119.70	7.30	18.80	26.10	47.80	132.80	180.60
SEm (±)	1.71	2.50	4.55	0.15	0.40	0.67	1.15	3.30	4.97
LSD (p=0.05)	5.08	7.47	13.66	0.44	1.17	2.00	3.42	9.89	14.88

vibrations in carbohydrates and phenolic compounds, while peaks around 2901–2923 cm⁻¹ reflected aliphatic C–H stretching. In the mid-infrared region, bands at about 1629–1637 cm⁻¹ were linked to C=O stretching and amide-associated vibrations. A distinct absorption band near 1500 cm⁻¹ was attributed to aromatic C=C stretching vibrations. In the fingerprint region, a peak observed at 1249 cm⁻¹ was attributed to P=O stretching vibrations, while the absorption band at 1074 cm⁻¹ corresponded to P–O stretching vibrations. Additionally, the peaks observed in the range of 571–523 cm⁻¹ were associated with P–O and P–O–P vibrations. Variations in the intensity of phosphorus-associated peaks were observed among the treatments. It was revealed that the control treatment (T₁: absolute control, N₀P₀K₀) and T₂ (100% recommended N and K) exhibited comparatively lower intensity in the phosphorus-related region. Among all treatments, T₁₀ (75% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 DAS + 100% recommended N and K) and T₁₁ (75% recommended P through DAP + nano-DAP seed dressing @ 10 mL L⁻¹ + foliar spray @ 0.4% at 35 and 55 DAS + 100% recommended N and K) exhibited more pronounced peaks in the regions associated with P=O, P–O, and P–O–P vibrations.

4 Discussion

4.1 Response of potato to varied phosphorus fertilization

The results clearly demonstrate that integrating nano-DAP with optimized DAP fertilization can reduce conventional phosphorus

inputs without compromising potato productivity. The performance of T₁₁ (75% P through DAP + seed dressing of nano-DAP @ 10 mL L⁻¹ water + foliar spray of nano-DAP @ 0.4% at 35 DAS + second spray @ 0.4% at 55 DAS + 100% recommended N and K), being comparable to T₆ (100% recommended DAP + 100% recommended N and K), indicates enhanced phosphorus bioavailability and uptake efficiency under nano-enabled nutrient management. This improvement is primarily attributed to reduced phosphate fixation in soil, as nano-sized particles exhibit limited interaction with Fe/Al oxides and Ca-carbonates, thereby maintaining a higher proportion of plant-available phosphorus in the rhizosphere (Najm and Al-Juthery, 2023; Arora and Khosla, 2024). Nano-sized particles applied via foliar spray can penetrate leaf tissues through stomatal openings and cuticular pores, enabling rapid entry into mesophyll cells and subsequent phloem-mediated translocation to actively growing plant tissues (Hong et al., 2021). The higher surface area, increased reactivity, and controlled-release behaviour of nano-DAP ensure a more synchronized nutrient supply during critical growth stages, minimizing losses and improving nutrient use efficiency (Beig et al., 2022; Dhiman et al., 2025; Subramani and Balakrishnan, 2026). Similar findings have been reported in wheat and chickpea, where reduced phosphorus levels supplemented with nano-DAP maintained yields equivalent to full recommended fertilization (Reddy et al., 2025; Khemshetty et al., 2024). The improved growth and physiological performance under nano-DAP treatments may be attributed to enhanced nutrient delivery, increased enzymatic activity, and improved nutrient uptake efficiency, which collectively promote cell division, metabolic activity, and protein synthesis (Keerthana et al., 2024; Reddy et al., 2024). This resulted in greater plant height, biomass accumulation, and photosynthetic efficiency through improved chlorophyll synthesis and nutrient uptake. The synergistic interaction

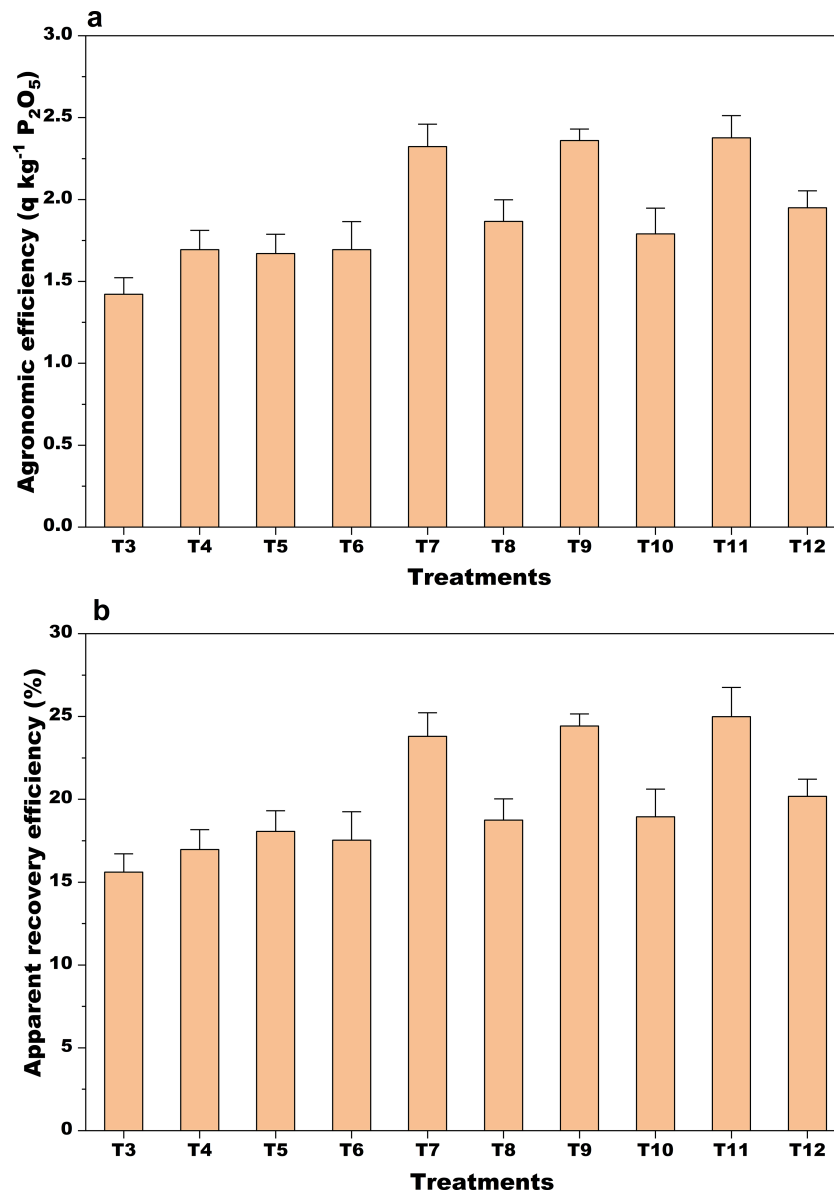


FIGURE 4

Agronomic efficiency (a) and apparent recovery efficiency (b) of potato under different phosphorus fertilization (pooled data of two years).

between soil-applied fertilizers and foliar nano-DAP ensured sustained nutrient availability and efficient assimilate partitioning, corroborating earlier reports (Mahachandramuki et al., 2023; Gopinath et al., 2025). Enhanced vegetative growth translated into improved yield attributes and tuber productivity. The combined application of conventional fertilizers and nano-DAP foliar spray increased nutrient absorption, photosynthetic activity, and assimilate translocation towards tubers, resulting in higher yields (Upadhyay et al., 2023; Sahoo et al., 2024). Foliar application further bypasses soil-related constraints such as phosphorus fixation, moisture stress, and pH limitations, ensuring rapid nutrient uptake (Henningesen et al., 2023; Gopinath et al., 2025). Improved nitrogen and phosphorus availability enhanced chlorophyll content, Rubisco activity, and dry matter accumulation, leading to efficient

partitioning of assimilates to tubers (Liu and Lal, 2015). These findings are in agreement with earlier studies reporting yield enhancement under integrated nano-DAP and conventional fertilization (Reddy et al., 2024, 2025; Mahalakshmi et al., 2024; Sahoo et al., 2024; Gopinath et al., 2025).

4.2 Nutrient uptakes, physiological and stress tolerance responses

Integrated application of nano-DAP with conventional DAP significantly enhanced N, P, and K uptake in potato haulms and tubers, primarily due to improved nutrient availability and absorption via combined soil and foliar application. Foliar nano-DAP prolonged N and P availability, synchronized nutrient supply with peak crop

TABLE 4 Effect of different phosphorus fertilization on leaf physiological and stress tolerance parameters of potato (pooled data of two years).

Treatments	SPAD	Chlorophyll content (mg g ⁻¹)	Membrane stability index (%)	Membrane injury index (%)	Relative water content (%)
T1	38.7	1.60	57.3	42.7	68.0
T2	45.5	2.05	71.0	29.0	80.7
T3	46.1	2.17	72.0	28.0	83.0
T4	46.3	2.27	73.3	26.7	84.7
T5	50.3	2.62	76.3	24.3	88.7
T6	53.1	2.70	79.3	20.0	91.0
T7	47.7	2.30	74.7	26.0	84.7
T8	48.4	2.37	76.0	24.0	85.0
T9	48.2	2.48	76.7	23.3	87.0
T10	51.1	2.63	74.3	24.3	88.7
T11	53.3	2.71	79.7	23.0	90.7
T12	53.1	2.73	79.3	20.0	91.0
SEm (±)	1.38	0.10	1.49	1.54	1.23
LSD (p=0.05)	4.03	0.30	4.35	4.50	3.61

demand, and reduced P fixation (Poudel et al., 2023; Gopinath et al., 2025). This synchronization supported efficient nutrient absorption, higher nutrient concentrations, and optimal dry matter production (Sahoo et al., 2024; Prakash et al., 2023). Reduced P without nano-DAP limited root development and nutrient uptake, which nano-DAP compensated, achieving uptake comparable to full recommended DAP. Physiological traits improved under integrated nano-DAP and conventional DAP, owing to enhanced P availability, photosynthetic activity, nutrient use efficiency, and sustained nutrient supply (Reddy et al., 2025; Subramani and Balakrishnan, 2026). Increased chlorophyll and SPAD values indicated better N and P

assimilation, while higher membrane stability and lower membrane injury reflected improved cellular integrity and reduced oxidative stress. Nano-DAP also enhanced foliar N and P assimilation in green gram (Ram et al., 2024) and improved SPAD values in rice bean (Nippani et al., 2026). Stress tolerance was markedly improved, with nano-fertilizers increasing antioxidant enzyme activities, reducing oxidative stress markers, and maintaining higher RWC and chlorophyll under salinity (Shoukat et al., 2025). Enhanced gas exchange and photosynthetic efficiency were reported in tomato and rice (Keerthana et al., 2024; Sweetey et al., 2024). The superior stress resilience and nutrient use efficiency resulted from nano-fertilizers'

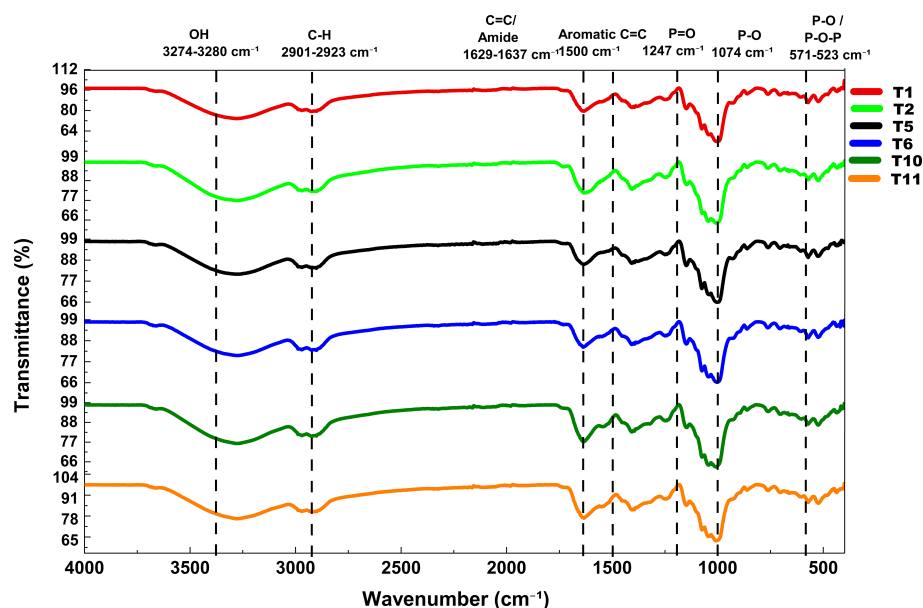


FIGURE 5 FTIR spectra in the 4000–400 cm⁻¹ range showing variations in characteristic functional groups and chemical composition among different phosphorus fertilization.

enhanced bioavailability, controlled nutrient release, and synchronization with crop demand (Gopinath et al., 2025; Shoukat et al., 2025). However, antioxidant enzyme activities (SOD, CAT, POD, and APX) were not assessed; thus, further biochemical and molecular studies are needed to elucidate nano-DAP-mediated stress tolerance and nutrient use efficiency in potato.

4.3 FTIR-based assessment of phosphorus functionalization under different phosphorus fertilization

FTIR spectral profiles revealed distinct differences in the intensities of functional groups associated with organic constituents and phosphorus-containing compounds among fertilizer treatments, indicating treatment-induced biochemical modifications in potato tissues. The broad absorption band in the O–H stretching region corresponds to polysaccharides, phenolic compounds, and structural carbohydrates, reflecting the fundamental plant biochemical composition (Kolathur et al., 2025). Peaks in the aliphatic C–H region are attributed to lipids and cellulose (Md Salim et al., 2021), while bands associated with carbonyl and amide groups indicate metabolically active compounds (Patel et al., 2025). These regions exhibited relatively minor variation across treatments, suggesting that the primary organic framework remained largely unaffected. In contrast, pronounced differences were observed in the fingerprint region, which is strongly associated with phosphorus-related functional groups. The presence of P=O, P–O–C, and P–O bands indicates both inorganic and organically bound phosphate compounds (Hossain and Ahmed, 2023). Increased intensity of these phosphate-related absorption bands generally reflects a greater abundance of phosphorus-containing functional groups in plant tissues, which corresponds with higher phosphorus accumulation and uptake observed under the nano-DAP treatments. Conventional DAP fertilization resulted in moderate expression of these phosphate-associated bands, confirming phosphorus incorporation into plant biochemical structures. However, nano-DAP-integrated treatments, particularly T10 and T11, exhibited stronger and sharper absorption bands, indicating enhanced association of phosphorus with organic matrices. This observation is consistent with the higher phosphorus uptake recorded under these treatments, indicating that increased phosphorus availability under nano-DAP fertilization facilitated greater biochemical incorporation of phosphorus into plant tissues. This enhancement can be attributed to the higher surface area and reactivity of nanoscale fertilizers, which improve phosphorus solubility, mobility, and absorption within plant tissues. The combined application of seed dressing and foliar nano-DAP likely facilitated efficient nutrient translocation and assimilation, leading to greater incorporation of phosphorus into metabolic compounds. These findings are consistent with improved nutrient-use efficiency reported under nano-fertilizer application (Singh et al., 2024b). The increased intensity of phosphate-related bands under nano-DAP treatments demonstrates enhanced phosphorus uptake and biochemical functionalization within the plant system, supporting its role in improving phosphorus use efficiency in potato.

5 Limitations and future implications of the study

The present study highlights the potential of strategically integrating nano-DAP with reduced yet balanced conventional phosphorus fertilization to sustain potato productivity; however, certain limitations should be considered. The experimental design did not include a nano-DAP-alone treatment at equivalent phosphorus rates, limiting precise separation of nano-DAP-derived phosphorus and supplementary nitrogen effects. Moreover, the experiment was conducted under the specific agroecological conditions of the north-western Indo-Gangetic Plains for two cropping seasons; therefore, the broader applicability of the findings requires validation across diverse soil types, climatic conditions, and long-term production systems. The FTIR analysis performed in this study was primarily qualitative, and quantitative spectral deconvolution or statistical comparison of peak intensities was not undertaken. In addition, although physiological traits were assessed, detailed investigations on antioxidant defence mechanisms, molecular responses, rhizosphere phosphorus dynamics, and the environmental fate of nano-DAP were beyond the scope of the present work.

Future research should therefore focus on multi-location and long-term experiments to validate the consistency of nano-DAP-based nutrient management strategies under diverse agroecosystems. Mechanistic studies examining soil-plant-nano interactions, phosphorus transformation pathways, and the persistence of nano-fertilizers in soil are also needed. Integration of nano-DAP with precision nutrient management approaches, site-specific fertilizer recommendations, and decision-support tools may further enhance phosphorus use efficiency. Additionally, economic evaluation and farmer participatory trials will be essential to assess the practicality, benefit-cost ratios, and scalability of nano-DAP adoption. Such integrated approaches could contribute to improved nutrient use efficiency, reduced dependence on conventional phosphatic fertilizers, and more sustainable potato production systems in the Indo-Gangetic Plains and comparable agroecosystems.

6 Conclusion

The present study demonstrated that the strategic integration of nano-diammonium phosphate (nano-DAP) with balanced conventional phosphorus fertilization significantly enhanced growth, yield, nutrient uptake, and physiological performance of potato. The treatment comprising 75% recommended phosphorus through DAP combined with nano-DAP (seed dressing and two foliar sprays at 35 and 55 DAS) performed comparably to the 100% recommended phosphorus dose, indicating improved phosphorus-use efficiency. The enhanced performance was associated with greater nutrient uptake, higher chlorophyll content, improved membrane stability, and better source-sink relationships. The combined use of nano-DAP with 75% of the recommended phosphorus dose enables a reduction of 25% in conventional phosphorus fertilizer without compromising yield, providing a promising strategy for improving phosphorus-use efficiency and promoting sustainable potato production.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

RG: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RB: Formal analysis, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. GS: Validation, Visualization, Writing – original draft, Writing – review & editing. SM: Conceptualization, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SW: Validation, Visualization, Writing – original draft, Writing – review & editing. RN: Writing – original draft, Writing – review & editing. CM: Writing – original draft, Writing – review & editing.

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