



SHORT COMMUNICATION

Integrated phosphorus management using nano-DAP and conventional phosphorus sources: Effects on chickpea performance and soil fertility in Inceptisols of Varanasi

Mounika Dhanavath, P.K Sharma* and Aditi Singh

Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi – 221005, Uttar Pradesh, India

*Corresponding author email: pkssac@gmail.com

Received : May 25, 2026

Revised : July 28, 2026

Accepted : August 03, 2026

Published : August 31, 2026

ABSTRACT

Chickpea (*Cicer arietinum* L.) is one of the most important pulse crops, valued for its high nutritional content and its ability to improve soil fertility through biological nitrogen fixation. However, phosphorus (P) deficiency remains a major constraint to chickpea production in Inceptisols due to low phosphorus availability and poor fertilizer use efficiency. To explore sustainable phosphorus management strategies, a net-house experiment was conducted during the Rabi season of 2021–22 at Varanasi, Uttar Pradesh. The study evaluated the combined effect of different organic and inorganic phosphorus sources with Nano-DAP on the growth, yield, nutrient uptake, grain quality, and post-harvest soil fertility of chickpea. The experiment was laid out in a Completely Randomized Design with ten treatments and three replications using chickpea variety Pusa-268. Treatments included conventional phosphorus fertilizers such as DAP, single superphosphate, rock phosphate, and phospho-enriched organic manure, applied individually or in combination with Nano-DAP through seed treatment and foliar application. The results showed that phosphorus application significantly improved crop growth and productivity compared with the control. The 100% recommended dose of fertilizers (RDF) recorded the highest values for growth, yield, nutrient uptake, and grain protein content. However, the treatment receiving 50% phosphorus through DAP along with Nano-DAP performed comparably to RDF for most growth and yield parameters, indicating that Nano-DAP can effectively supplement conventional phosphorus fertilizers without compromising productivity. Post-harvest soil analysis revealed no significant changes in soil pH or electrical conductivity, confirming that the treatments did not adversely affect soil health. Integrated phosphorus treatments, particularly those combined with organic manure and Nano-DAP, improved soil organic carbon and increased the availability of nitrogen, phosphorus, and sulphur. Overall, integrating Nano-DAP with conventional phosphorus sources offers a promising and sustainable approach for enhancing chickpea productivity while improving soil fertility and phosphorus use efficiency in Inceptisols.

Keywords: Nano-DAP, Yield attributes, Protein content, Integrated nutrient management, Post-harvest soil fertility

INTRODUCTION

Chickpea (*Cicer arietinum* L.), popularly known as Bengal gram, is one of the oldest and most widely cultivated pulse crops in the world. Believed to have

originated in the Middle East, it is now extensively grown in countries such as India, Australia, Pakistan, Turkey, Myanmar, and Ethiopia. India is the largest producer and consumer of chickpea,

contributing nearly one-fourth of global pulse production. The crop is widely cultivated across diverse agro-climatic regions owing to its adaptability to low-input farming systems, drought tolerance, and ability to fix atmospheric nitrogen through symbiotic association with *Rhizobium*. Besides enriching soil fertility, chickpea serves as an important component of sustainable cropping systems, particularly under rainfed conditions.

Chickpea is often regarded as a “poor man’s meat” because of its high nutritional value and affordability. The grains contain approximately 20–25% protein, 55–60% carbohydrates, 5–6% fat, and are rich in essential minerals such as calcium, phosphorus, and iron, along with several vitamins (Prasad, 2012). In addition to being consumed as whole grains, split dal, flour, roasted seeds, and green vegetables, chickpea straw is a nutritious livestock feed. Thus, the crop contributes significantly to food and nutritional security, livestock production, and the livelihood of millions of smallholder farmers.

Despite its importance, chickpea productivity remains below its potential in many parts of India. Increasing demand for pulses, shrinking cultivable land, declining soil fertility, and inefficient nutrient management have widened the gap between production and consumption. Improving nutrient-use efficiency while maintaining soil health has therefore become a major challenge for sustainable chickpea production.

Among the essential plant nutrients, phosphorus (P) plays a pivotal role in chickpea growth and productivity. It is second only to nitrogen in terms of its importance for plant development (Raghothama, 1999). Phosphorus is involved in several fundamental physiological and biochemical processes, including energy transfer, photosynthesis, respiration, cell division, root development, flowering, seed formation, and biological nitrogen fixation. It forms an integral part of ATP, DNA, RNA, and phospholipids, making it indispensable for plant metabolism. In legumes such as chickpea, adequate phosphorus nutrition promotes vigorous root growth, enhances nodulation, improves nitrogen fixation, increases nutrient uptake, and ultimately leads to higher grain yield and improved seed quality.

However, phosphorus management remains one of the major constraints in agricultural soils. Although soils generally contain substantial amounts

of total phosphorus, only a small proportion is available for plant uptake because most of it becomes fixed by calcium, iron, or aluminium compounds depending on soil characteristics. This problem is particularly severe in the Inceptisols of the Indo-Gangetic Plains, where phosphorus fixation substantially reduces fertilizer-use efficiency. Consequently, crops are often unable to utilize a large fraction of the applied phosphorus, resulting in low recovery efficiency, increased fertilizer costs, and depletion of finite phosphate resources.

The excessive dependence on conventional chemical fertilizers has also raised concerns regarding soil degradation, nutrient imbalance, declining soil organic carbon, and environmental sustainability. Continuous use of mineral fertilizers without adequate organic inputs can adversely affect soil physical, chemical, and biological properties, ultimately reducing long-term productivity. Therefore, modern nutrient management strategies should aim not only to maximize crop yield but also to maintain or improve soil health. Soil properties such as pH, electrical conductivity, organic carbon, and the availability of essential nutrients determine nutrient cycling, microbial activity, and overall soil productivity. Evaluating the residual effects of fertilizer practices on these soil properties is therefore essential for developing sustainable production systems.

Integrated nutrient management has emerged as a promising approach to address these challenges. The combined use of organic and inorganic nutrient sources helps maintain soil fertility while improving nutrient-use efficiency. Organic amendments such as phospho-enriched organic manure enhance soil organic matter, stimulate microbial activity, improve nutrient retention, and gradually release nutrients throughout the crop growth period. They can also reduce phosphorus fixation by forming stable complexes with soil minerals, thereby increasing phosphorus availability to plants and improving the residual fertility of soil.

Recent advances in nanotechnology have further opened new opportunities for improving fertilizer efficiency. Nano-fertilizers are designed to deliver nutrients in a controlled and targeted manner through nanoscale formulations that possess high surface area and enhanced reactivity (Rai *et al.*, 2012). Among these, Nano-DAP has attracted considerable attention as an innovative phosphorus fertilizer capable of improving phosphorus

availability and nutrient-use efficiency. Due to their extremely small particle size, Nano-DAP formulations facilitate efficient nutrient absorption and translocation within plants through seed treatment and foliar application (Lv et al., 2019). Their controlled-release characteristics help synchronize nutrient supply with crop demand, thereby minimizing fixation losses, reducing fertilizer requirements, and improving crop productivity with lower environmental impact.

While the beneficial effects of Nano-DAP on crop growth have received increasing attention, information on its integration with conventional phosphorus fertilizers and organic phosphorus sources, particularly under the Inceptisols of eastern Uttar Pradesh, remains limited. Moreover, studies simultaneously evaluating plant growth, yield, grain quality, nutrient uptake, and post-harvest soil fertility under integrated phosphorus management are still scarce. Understanding both crop response and changes in soil nutrient status is essential for developing sustainable phosphorus management strategies that enhance productivity without compromising soil health.

Therefore, the present investigation was undertaken to evaluate the combined effect of organic and inorganic phosphorus sources along with Nano-DAP on the growth, yield, protein content, nutrient uptake, and post-harvest soil fertility of chickpea grown in the Inceptisols of Varanasi. The study also assessed changes in soil pH, electrical conductivity, organic carbon, and the availability of nitrogen, phosphorus, potassium, and sulphur following different phosphorus management practices. The findings are expected to provide scientific evidence for developing efficient, economically viable, and environmentally sustainable phosphorus management strategies that improve both chickpea productivity and long-term soil fertility.

MATERIALS AND METHODS

The present investigation was carried out during the Rabi season of 2021–22 under net-house conditions at the Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University (BHU), Varanasi, Uttar Pradesh, India. The experiment was conducted to evaluate the effect of integrating Nano-DAP with different organic and inorganic

phosphorus sources on the growth, yield, grain quality, nutrient content, nutrient uptake of chickpea, and the chemical properties of post-harvest soil. The experimental soil was collected from the Agricultural Research Farm of the Institute of Agricultural Sciences, BHU, situated approximately 10 km from Varanasi city in the Middle Gangetic Plains of eastern Uttar Pradesh. The research farm is geographically located at 25°26' N latitude and 82°59' E longitude, with an elevation of 128.93 m above mean sea level. The soil belongs to the Inceptisol order and represents the alluvial soils extensively distributed across the Indo-Gangetic Plains.

The climate of the experimental area is semi-arid to sub-humid with distinct summer, monsoon, and winter seasons. The southwest monsoon generally extends from June to September, contributing an average annual rainfall of approximately 1100 mm, while the annual potential evapotranspiration is nearly 1500 mm. The maximum temperature during summer ranges between 39 and 43°C, whereas winter temperatures may fall to about 9–10°C. Relative humidity varies from nearly 30% during the dry season to around 82% during the monsoon. These agro-climatic conditions are favourable for chickpea cultivation during the Rabi season and provide an ideal environment for evaluating different phosphorus management practices.

A pot experiment was conducted using chickpea (*Cicer arietinum* L.) variety Pusa-268 as the test crop. Bulk surface soil collected from the research farm was air-dried under shade, gently crushed, and passed through a 2-mm sieve to obtain a homogeneous soil sample. Polythene-lined pots were filled with 10 kg of processed soil on a dry-weight basis. The experiment was laid out in a Completely Randomized Design (CRD) comprising ten treatments with three replications, resulting in a total of thirty experimental units. The recommended dose of fertilizers (RDF) equivalent to 10:30:10 mg kg⁻¹ soil (N:P) was applied according to the treatment requirements. Nitrogen was supplied through urea, phosphorus through different fertilizer sources, namely diammonium phosphate (DAP), rock phosphate (RP), phospho-enriched organic manure (PROM), and single superphosphate (SSP), while potassium was supplied through muriate of potash (MOP).

The treatments consisted of different combinations of conventional phosphorus fertilizers and Nano-DAP. Treatment T_1 served as the unfertilized control, whereas T_2 received the recommended dose of fertilizers. Treatments T_3 and T_4 consisted of 50% phosphorus supplied through DAP and the remaining 50% through Nano-DAP, with Nano-DAP applied as a seed treatment followed by one and two foliar sprays, respectively. Similarly, treatments T_5 and T_6 received 50% phosphorus through rock phosphate combined with Nano-DAP, while treatments T_7 and T_8 involved the application of 50% phosphorus through phospho-enriched organic manure integrated with Nano-DAP. Treatments T_9 and T_{10} consisted of 50% phosphorus supplied through single superphosphate along with Nano-DAP applied as seed treatment followed by one and two foliar sprays, respectively. This treatment structure was designed to compare the efficiency of different organic and inorganic phosphorus sources integrated with Nano-DAP in improving crop performance and maintaining soil fertility.

The required quantities of basal fertilizers were thoroughly incorporated into the soil before sowing to ensure uniform nutrient availability during the initial stages of crop growth. Chickpea seeds were then sown under controlled net-house conditions according to the experimental layout. Nano-DAP was applied as a seed treatment before sowing, while foliar applications were carried out at 30 and 60 days after sowing (DAS) depending on the treatment schedule. After germination, five healthy and uniform plants were maintained in each pot to ensure a uniform plant population throughout the experimental period. All recommended agronomic practices, including irrigation, weed management, and plant protection measures, were followed uniformly to maintain optimum crop growth and to avoid any external factors that could influence treatment responses. The crop was harvested at physiological maturity for recording observations on growth, yield, nutrient uptake, grain quality, and post-harvest soil properties.

Growth observations were recorded periodically during crop development. Plant height was measured from the soil surface to the tip of the main shoot at 30, 60, and 90 days after sowing, while the number of primary branches per plant was recorded at 30 and 60 days after sowing. At maturity, important yield attributes including the number of pods per

plant, number of grains per pod, and 1000-seed weight (test weight) were recorded. Grain and straw yields were determined after harvesting and threshing the crop and expressed on a per-pot basis. The harvest index (HI) was calculated by dividing grain yield by biological yield and expressing the value as a percentage.

For plant nutrient analysis, representative grain and straw samples from each treatment were collected after harvest. The samples were thoroughly washed with 0.2% detergent solution, followed by 0.1 N hydrochloric acid and distilled water to remove adhering impurities. The cleaned samples were oven-dried at 60°C until constant weight and subsequently ground in a Wiley mill for chemical analysis. Total nitrogen content was estimated using the Kjeldahl digestion method. Phosphorus concentration was determined after di-acid digestion (HNO_3^- ; 3:1) following the method described by Jackson (1973) using the vanado-molybdate yellow colour method, whereas potassium concentration was measured from the same digest using a flame photometer. Nutrient uptake by grain and straw was calculated by multiplying nutrient concentration with the corresponding dry matter yield and expressed as $\mu\text{g pot}^{-1}$. Grain protein content was calculated by multiplying nitrogen concentration with the standard conversion factor of 6.25.

Following crop harvest, soil samples were collected separately from each pot to evaluate the residual effects of different phosphorus management practices on soil fertility. The samples were air-dried at room temperature, gently crushed, and passed through a 2-mm sieve. A representative portion was further ground and sieved through 0.5 mm for laboratory analysis. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-water suspension using digital pH and EC meters following the procedure described by Sparks (1996). Soil organic carbon was estimated by the Walkley and Black (1934) wet oxidation method. Available nitrogen was determined using the alkaline potassium permanganate method of Subbiah and Asija (1956). Available phosphorus was estimated by Olsen's method (Olsen *et al.*, 1954) using a spectrophotometer at 882 nm, while available potassium was extracted with 1 N neutral ammonium acetate and measured using a flame photometer following Hanway and Heidel (1952). Available sulphur was also determined using standard analytical procedures to assess the residual fertility status of the soil after harvest.

The data generated on growth parameters, yield attributes, grain and straw yield, harvest index, nutrient content, nutrient uptake, grain protein content, and post-harvest soil chemical properties were subjected to statistical analysis following the principles of a Completely Randomized Design (CRD). Analysis of variance (ANOVA) was performed to evaluate the significance of treatment effects, and treatment means were compared at the 5% probability level following the procedure described by Federer (1967). The statistical analysis enabled a reliable assessment of the influence of integrating Nano-DAP with different organic and inorganic phosphorus sources on chickpea productivity, nutrient use efficiency, and post-harvest soil fertility under Inceptisol conditions.

RESULTS AND DISCUSSION

The present investigation clearly demonstrated that phosphorus management significantly influenced the growth, productivity, nutrient acquisition, grain quality, and overall performance of chickpea grown in the Inceptisols of Varanasi. Application of phosphorus through conventional fertilizers as well as in combination with Nano-DAP resulted in marked improvement over the unfertilized control, indicating the importance of adequate phosphorus nutrition for optimum crop growth. Although the recommended dose of fertilizers (RDF) recorded the highest values for most of the observed parameters, treatments integrating Nano-DAP with conventional phosphorus fertilizers, particularly T₄ (50% P through DAP + Nano-DAP seed treatment with two foliar sprays) and T₃ (50% P through DAP + Nano-DAP seed treatment with one foliar spray), performed comparably for several growth, yield, and quality attributes. These observations suggest that Nano-DAP can effectively supplement conventional phosphorus fertilizers and improve phosphorus use efficiency under Inceptisol conditions.

Growth Performance

Growth is one of the most reliable indicators of crop response to nutrient availability, and the results of the present study revealed that phosphorus application had a significant positive influence on vegetative development throughout the crop growth period. Plant height increased steadily from the initial growth stage to crop maturity under all

treatments, but the magnitude of increase varied considerably depending upon the source and method of phosphorus application. The tallest plants were recorded under RDF, followed closely by T₄ and T₃, whereas the control treatment consistently exhibited the lowest plant height.

The enhanced plant growth observed under phosphorus fertilization can be attributed to the fundamental role of phosphorus in plant metabolism. Phosphorus is essential for ATP synthesis, nucleic acid formation, energy transfer, photosynthesis, and cell division. It also promotes rapid root development during the early stages of crop growth, enabling plants to exploit a larger volume of soil for water and nutrient absorption. A well-developed root system not only improves nutrient acquisition but also enhances the plant's ability to withstand temporary moisture stress, thereby supporting sustained vegetative growth throughout the growing season. The encouraging performance of Nano-DAP-based treatments indicates that nano-formulated phosphorus improved nutrient availability by reducing fixation losses and providing a more sustained supply of phosphorus. Unlike conventional phosphorus fertilizers, which often become unavailable soon after application due to fixation with calcium compounds in alkaline soils, Nano-DAP appears to maintain phosphorus in a more available form for a longer duration. The gradual release of nutrients likely synchronized phosphorus availability with crop demand, resulting in continuous physiological activity and improved plant growth.

A similar trend was observed for the number of branches per plant. Branch production increased significantly under phosphorus-applied treatments compared with the control, with RDF recording the highest number of branches, followed closely by Nano-DAP integrated treatments. Increased branching contributes directly to canopy development and ultimately determines the photosynthetic capacity of the crop. Better phosphorus nutrition promotes active meristematic growth, enhances chlorophyll formation, and stimulates enzymatic activity involved in carbohydrate synthesis. Consequently, plants develop a larger canopy capable of producing greater quantities of assimilates required for reproductive development.

Yield Attributes and Crop Productivity

The beneficial effect of phosphorus application was further reflected in yield attributes, including pods per plant, grains per pod, and test weight. These parameters showed significant improvement over the control, with RDF recording the highest values, while Nano-DAP integrated treatments remained statistically comparable for most observations.

Pod formation represents one of the most critical stages in determining final grain yield. Adequate phosphorus availability during flowering and pod initiation improves flower retention, reduces floral abortion, and enhances pod setting. The larger number of pods observed under phosphorus-applied treatments therefore reflects improved reproductive efficiency resulting from balanced nutrient availability. The comparatively better performance of Nano-DAP treatments suggests that the continuous availability of phosphorus during reproductive growth supported efficient assimilate translocation and sink development.

The number of grains per pod also improved with phosphorus application. Efficient grain formation depends upon uninterrupted nutrient supply during flowering and seed development. Phosphorus enhances the transport of photosynthates from source leaves to developing reproductive organs through its involvement in ATP-mediated energy transfer. As a result, better fertilization, improved embryo development, and enhanced grain filling contribute to increased grain number and seed size. Test weight followed a trend similar to other yield attributes. The highest test weight was recorded under RDF, while T_4 and T_3 remained statistically similar. Higher test weight reflects efficient grain filling and greater accumulation of dry matter in seeds. Since phosphorus plays a major role in carbohydrate metabolism and translocation, improved phosphorus availability under Nano-DAP treatments likely facilitated better movement of assimilates into developing grains, resulting in heavier seeds.

The combined improvement in these yield components ultimately contributed to higher grain yield. Grain yield increased significantly under all phosphorus-applied treatments compared with the control, with RDF producing the maximum yield. However, the yield obtained under T_4 and T_3 remained statistically comparable to RDF, indicating that Nano-DAP successfully compensated for the

reduction in conventional phosphorus fertilizer. This observation is particularly important because it demonstrates the possibility of reducing the application of conventional phosphorus fertilizers without sacrificing productivity. Straw yield also increased significantly following phosphorus application. Higher straw yield indicates greater biomass production resulting from improved vegetative growth, enhanced photosynthesis, and efficient nutrient utilization. Increased biomass accumulation reflects the ability of the crop to convert available resources into structural and reproductive tissues more efficiently under balanced phosphorus nutrition.

Harvest index, which represents the efficiency with which total biomass is converted into economic yield, also improved under phosphorus-applied treatments. Higher harvest index values observed under RDF and Nano-DAP treatments indicate more efficient partitioning of photosynthates towards grain production. This suggests that balanced phosphorus nutrition not only increased total biomass but also enhanced the physiological efficiency of the crop by favouring reproductive growth over excessive vegetative development.

Nutrient Concentration, Uptake and Grain Quality

One of the most significant effects of phosphorus application was the improvement in nutrient concentration and nutrient uptake. The concentrations of nitrogen, phosphorus, potassium, and sulphur in both grain and straw increased substantially under phosphorus-fertilized treatments. The RDF treatment recorded the highest nutrient concentrations, although Nano-DAP integrated treatments remained statistically comparable for most nutrients.

The increase in nitrogen concentration is closely associated with improved nodulation and biological nitrogen fixation in chickpea. Phosphorus is known to stimulate nodule formation and enhance the activity of nitrogen-fixing bacteria, thereby increasing nitrogen availability within the plant. Improved nitrogen assimilation subsequently promotes chlorophyll synthesis, enzyme activity, and protein formation, all of which contribute to higher crop productivity.

Phosphorus concentration itself showed the greatest response to treatment application, reflecting improved nutrient availability and efficient uptake

under balanced fertilization. Nano-DAP likely reduced phosphorus fixation and maintained a continuous supply of available phosphorus throughout the crop growth period. The nanoscale particles possess a larger reactive surface area and improved mobility, allowing nutrients to be absorbed more efficiently and transported rapidly within plant tissues. The concentrations of potassium and sulphur also increased under integrated nutrient management. Better root development under phosphorus fertilization enhanced the absorption of these nutrients from the soil. Improved nutrient balance within the plant further supported metabolic activities, contributing to healthier crop growth and improved productivity.

The trends observed for nutrient uptake closely followed those recorded for nutrient concentration. Total uptake of nitrogen, phosphorus, potassium, and sulphur increased significantly under phosphorus application due to the combined effect of higher nutrient concentration and increased biomass production. Enhanced root proliferation, improved nutrient availability, and greater dry matter accumulation collectively contributed to superior nutrient uptake under RDF and Nano-DAP integrated treatments. Grain quality also improved considerably following phosphorus application. Grain protein content increased significantly compared with the control, with RDF recording the highest protein percentage, followed closely by Nano-DAP treatments. Protein synthesis is closely associated with nitrogen metabolism, which in turn depends on adequate phosphorus availability. By improving biological nitrogen fixation and facilitating efficient nitrogen assimilation, phosphorus indirectly promoted amino acid synthesis and protein accumulation in developing grains. Consequently, integrated phosphorus management enhanced not only grain yield but also its nutritional quality, making chickpea a more valuable source of dietary protein. Overall, the results obtained during the present investigation clearly demonstrate that balanced phosphorus nutrition substantially improved vegetative growth, reproductive development, nutrient uptake, and grain quality of chickpea. Although RDF remained the best-performing treatment, the comparable performance of T₄ and T₃ indicates that Nano-DAP can successfully supplement conventional phosphorus fertilizers and significantly improve phosphorus use efficiency under Inceptisol conditions.

Post-Harvest Soil Fertility

Besides improving crop growth and productivity, phosphorus management also influenced the fertility status of the soil after harvest. Assessing post-harvest soil properties is important because an efficient nutrient management strategy should not only increase crop yield but also maintain or improve soil health for subsequent cropping seasons. The results of the present study showed that integrating conventional phosphorus fertilizers with Nano-DAP and organic phosphorus sources had a positive influence on residual soil fertility without adversely affecting the chemical properties of the soil.

Soil reaction (pH) remained almost unchanged across all treatments, with only marginal differences observed between fertilized and unfertilized pots. The slightly alkaline nature of the experimental soil was maintained throughout the study, indicating that the application of different phosphorus sources, either alone or in combination with Nano-DAP, did not significantly alter soil reaction. The absence of any appreciable change in soil pH may be attributed to the high buffering capacity of Inceptisols, which minimizes short-term fluctuations even after fertilizer application. This finding suggests that Nano-DAP and integrated phosphorus management practices can be adopted without creating undesirable changes in soil acidity or alkalinity. Electrical conductivity (EC) also showed very little variation among treatments and remained within the non-saline range after crop harvest. The consistently low EC values indicate that none of the phosphorus sources contributed to excessive salt accumulation in the soil. This observation is particularly encouraging because it confirms that the repeated use of Nano-DAP along with conventional fertilizers is unlikely to create salinity-related problems under normal crop production conditions. Maintaining a stable EC is essential for sustaining root growth, nutrient uptake, and microbial activity in agricultural soils. A slight improvement in soil organic carbon was observed under integrated nutrient management, particularly in treatments receiving phospho-enriched organic manure (PROM) along with Nano-DAP. Although the increase was statistically non-significant, the positive trend highlights the importance of incorporating organic nutrient sources into fertilizer management programmes. Organic amendments supply carbon-rich materials that improve soil aggregation, stimulate microbial activity, and

support nutrient cycling. The gradual decomposition of these materials also contributes to the build-up of soil organic matter, which plays an important role in enhancing soil fertility and improving nutrient retention. Therefore, integrating organic phosphorus sources with Nano-DAP offers additional benefits beyond nutrient supply by contributing to long-term soil health. Residual available nitrogen in the soil showed an increasing trend under phosphorus-applied treatments compared with the control. Higher available nitrogen observed in Nano-DAP integrated treatments may be associated with improved biological nitrogen fixation, greater microbial activity, and better nutrient cycling during crop growth. Enhanced phosphorus availability promotes nodulation and increases the efficiency of nitrogen fixation in legumes, allowing more nitrogen to remain within the soil-plant system after harvest. Improved root growth under balanced fertilization may also have contributed to greater retention of nitrogen in the rhizosphere, thereby increasing residual soil fertility. Among all the soil nutrients studied, available phosphorus responded most markedly to the applied treatments. The RDF treatment recorded the highest residual phosphorus content, followed closely by treatments receiving DAP in combination with Nano-DAP. This increase reflects the direct contribution of phosphorus fertilizers to the available nutrient pool as well as the ability of Nano-DAP to reduce phosphorus fixation. In alkaline Inceptisols, a large proportion of applied phosphorus is rapidly converted into insoluble forms through reactions with calcium compounds, thereby limiting its availability to crops. The relatively higher residual phosphorus observed under Nano-DAP treatments suggests that nano-formulations maintained phosphorus in a more plant-available form by slowing nutrient release and reducing fixation losses. This improvement in phosphorus availability is particularly valuable in phosphorus-deficient soils where fertilizer efficiency is generally low. Available potassium exhibited comparatively smaller changes among treatments. Since potassium was applied uniformly to all treatments, major differences were not expected. Nevertheless, slightly higher potassium levels recorded under integrated nutrient management may be attributed to improved root activity and enhanced nutrient cycling. Better root proliferation under adequate phosphorus nutrition increases soil exploration and promotes efficient uptake and redistribution of potassium within the soil-plant system. Residual sulphur

content showed a significant improvement in treatments receiving single superphosphate (SSP), either alone or in combination with Nano-DAP. This response is expected because SSP contains sulphur in addition to phosphorus. The relatively higher sulphur content observed in these treatments indicates that fertilizer source plays an important role in determining the residual nutrient status of the soil. Since sulphur is an essential constituent of amino acids and proteins, maintaining adequate sulphur availability is particularly important for pulse crops such as chickpea. Overall, the post-harvest soil analysis revealed that integrated phosphorus management maintained favourable soil conditions while improving the availability of essential nutrients. The absence of adverse changes in soil pH and EC further confirms that Nano-DAP can be incorporated into nutrient management programmes without compromising soil quality.

Integrated Plant-Soil Response

One of the important outcomes of the present investigation is the close relationship observed between crop performance and soil fertility. Treatments that produced better growth and yield also maintained comparatively higher levels of available nutrients after harvest, indicating improved nutrient use efficiency. Enhanced phosphorus availability supported vigorous root development, which in turn increased nutrient absorption, biomass accumulation, and grain production. At the same time, balanced nutrient management minimized nutrient losses and contributed to maintaining residual fertility in the soil. The beneficial effect of Nano-DAP appears to result from its ability to synchronize phosphorus availability with crop demand. Conventional phosphorus fertilizers often release nutrients rapidly, making them susceptible to fixation in alkaline soils before plants can utilize them efficiently. Nano-DAP, however, provides nutrients gradually, ensuring a more continuous supply throughout the crop growth period. This sustained nutrient availability supports active physiological processes such as photosynthesis, enzyme activity, carbohydrate metabolism, and protein synthesis, ultimately improving both yield and grain quality.

The improved nutrient uptake observed under Nano-DAP treatments also reflects better interaction between plant roots and the soil environment. Greater root proliferation increases the volume of

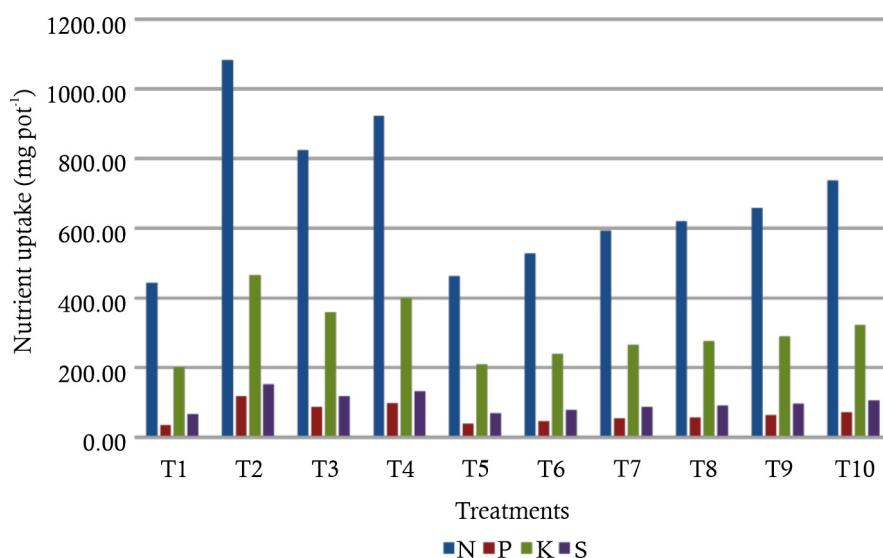


Fig. 1. Effect of Nano DAP application on nutrient uptake by grain of Chickpea

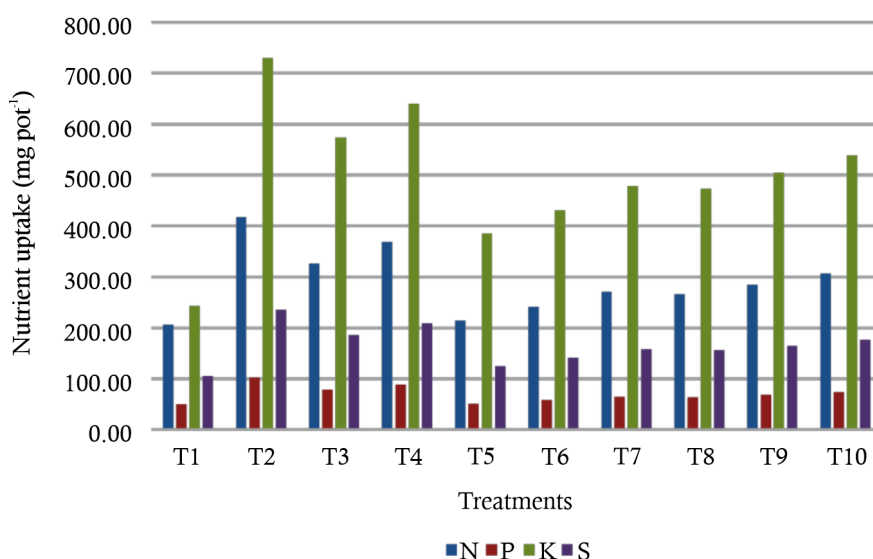


Fig. 2. Effect of Nano DAP application on nutrient uptake by straw of Chickpea

soil explored by the crop, enhancing the absorption of relatively immobile nutrients such as phosphorus. Improved root activity also stimulates rhizosphere microbial populations, which contribute to nutrient mineralization and improved nutrient availability. These combined effects explain why Nano-DAP integrated treatments produced crop performance comparable to RDF despite receiving only half of the conventional phosphorus dose.

Agronomic Significance

The findings of the present investigation have important implications for sustainable nutrient management in chickpea cultivation. Phosphorus is

one of the costliest and least efficiently utilized plant nutrients because a large proportion of applied phosphorus becomes unavailable shortly after application. Improving phosphorus use efficiency is therefore essential for reducing production costs and conserving finite phosphate resources. The present study demonstrated that integrating Nano-DAP with conventional phosphorus fertilizers substantially improved crop performance while maintaining soil fertility. Treatments receiving only 50% phosphorus through conventional DAP along with Nano-DAP produced growth, yield, nutrient uptake, and grain quality that were comparable to RDF for many parameters. This indicates that Nano-DAP can

partially replace conventional phosphorus fertilizers without causing any significant reduction in productivity.

Such an approach offers several practical advantages. Reduced dependence on chemical phosphorus fertilizers lowers input costs, improves fertilizer use efficiency, and minimizes environmental risks associated with excessive phosphorus application. At the same time, the inclusion of organic phosphorus sources contributes to improved soil organic matter, enhanced microbial activity, and better nutrient cycling. Together, these benefits make integrated phosphorus management a promising strategy for sustainable pulse production under phosphorus-fixing soils.

CONCLUSIONS

Adequate phosphorus availability enhanced vegetative growth, reproductive development, nutrient uptake, and protein synthesis, leading to significant improvements in chickpea yield and quality. Simultaneously, integrated nutrient management maintained favourable soil chemical properties and improved the availability of essential nutrients after harvest. Although the recommended dose of fertilizers consistently produced the highest values for most parameters, the performance of Nano-DAP integrated treatments was remarkably close. This finding demonstrates the ability of Nano-DAP to improve phosphorus use efficiency through controlled nutrient release and reduced fixation losses. The study therefore provides strong evidence that Nano-DAP can serve as an effective supplement to conventional phosphorus fertilizers in chickpea cultivation. Integrated application of Nano-DAP with conventional and organic phosphorus sources proved to be an effective nutrient management strategy for chickpea. While RDF remained the most productive treatment, Nano-DAP integrated treatments, particularly those combining 50% phosphorus through DAP with Nano-DAP, maintained comparable growth, yield, nutrient uptake, grain protein content, and residual soil fertility. These findings indicate that Nano-DAP has considerable potential to reduce the requirement for

conventional phosphorus fertilizers while sustaining crop productivity and soil health. Therefore, the integration of Nano-DAP with existing nutrient management practices may provide a practical and environmentally sustainable approach for improving chickpea production in the phosphorus-fixing Inceptisols of the Indo-Gangetic Plains.

REFERENCES

- Federer W. T. (1967). *Experimental design*. Calcutta: Oxford and IBH Publishing Company.
- Hanway, J.J., Heidal, H. (1952). Soil analysis methods as used in Iowa State College Soil Testing Laboratory. *Iowa State College of Agriculture Bulletin*, 57, 1-31.
- Jackson, M.L. (1973). *Soil Chemical Analysis*. Asia publishing house, New Delhi.
- Lv, J., Christie, P. and Zhang, S. (2019). Uptake, translocation, and transformation of metal-based nanoparticles in plants: Recent advances and methodological challenges. *Environmental Science: Nano*, 6(1), 41–59.
- Olsen, S.R., Cole, C.V. and Watanabe, F.S. (1954). Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. USDA Circular No. 939, US Government Printing Office, Washington DC.
- Prasad, R. (2011). Nitrogen and food grain production in India. *Indian Journal of Fertilisers*, 7(12), 66–76.
- Raghothama, K.G. (1999). Phosphate acquisition. *Annual Review of Plant Physiology and Plant Molecular Biology*, 50, 665–693.
- Rai, V., Acharya, S. and Dey, N. (2012). Implications of Nanobiosensors in Agriculture. *Journal of Biomaterials and Nanobiotechnology*, 3(2A), 315–324.
- Sparks, J.P., Campbell, G.S. and Black, A.R. (2001). Water content, hydraulic conductivity, and ice formation in winter stems of *Pinus contorta*: a TDR case study. *Oecologia*, 127(4), 468-475.
- Subbiah, B.V. and Asija, G.L. (1956). A Rapid Procedure for the Estimation of Available Nitrogen in Soils. *Current Science*, 25, 259-260.
- Walkley, A. and Black, T.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37, 29-38.