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Enhancing Soybean (*Glycine max* L. Merrill.) Productivity through Varied Phosphorus Levels and Foliar Application of Nano-DAP

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ABSTRACT

A field experiment was conducted at AICRP on soybean, MARS, UAS, Dharwad, Karnataka during *kharif*, 2023 (July to October) to study the response of soybean through varied phosphorus levels and foliar application of Nano-DAP. The experiment was replicated thrice in a split-plot design with three main plots and four subplots. Application of 100% recommended dosage of phosphorus. recorded significantly higher plant height (42.15 cm), number of branches plant^{-1} (6.73), leaf area (12.23 dm^2 plant^{-1}), leaf area index (4.07), total dry matter accumulation/plant (28.78 g), SPAD value (50.10), number of nodules (47.08 plant^{-1}), number of pods (45.26 plant^{-1}), seed yield plant^{-1} (15.88 g), 100 seed weight (15.20 g), seed yield (2564 kg ha^{-1}), haulm yield (3222 kg ha^{-1}), net returns (₹ 84,517 ha^{-1}) and B-C ratio (2.94) over 75% recommended dosage of phosphorus and control. Among foliar nutrition, foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS recorded significantly higher plant height (39.77 cm), number of branches plant^{-1} (6.34), leaf area (11.20 dm^2 plan^{-1}), leaf area index (3.75), total dry matter accumulation plant^{-1} (26.27 g), SPAD value (47.92), number of nodules (40.60 plant^{-1}), number of pods plant^{-1} (41.86), seed yield plant^{-1} (14.55 g), 100 seed weight (14.74 g), seed yield (2330 kg ha^{-1}), haulm yield (2922 kg ha^{-1}), net returns (₹ 71,513 ha^{-1}) and B-C ratio (2.59) over no foliar applications. Among the interaction effects, application of 100% RDP+foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (M_1S_3) recorded significantly higher productivity, quality parameters and economic returns of soybean crop.

KEYWORDS: Economics, nano-DAP, phosphorus use efficiency, productivity, soybean

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Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

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1. INTRODUCTION

Soybean (*Glycine max* L. Merrill) is a major oilseed and legume crop globally, contributing 25% of the world's edible oil and serving as a primary protein source for livestock feed. Soybean meal is widely used in poultry and aquaculture diets due to its high nutritional value, containing around 40% protein and 20% oil (Somanagouda et al., 2024). This rich composition has earned it the reputation of a "wonder crop." Globally, soybean covers an area of 140.00 m ha and annual production of 394.96 m t with a productivity of 2820 kg ha^{-1} (Anonymous, 2023a). In India, it occupies an area of 13.00 mha with a production of 12.56 m t and productivity of 970 kg ha^{-1} (Anonymous, 2023b). In Karnataka, soybean is grown in an area of 0.381 m ha with production of 0.437 mt and productivity of 1147 kg ha^{-1} (Anonymous, 2023c). Soybean production is often limited by biotic and abiotic stresses and poor crop management, highlighting the need for effective nutrient strategies. Proper nutrient management is essential for maximizing yields by ensuring plants receive key nutrients without significant losses (Biradar et al., 2023). Traditional soil application faces issues like leaching, runoff, and fixation, reducing fertilizer efficiency. Foliar nutrition helps overcome these challenges, especially for macronutrients like nitrogen, phosphorus, and potassium (Abisankar et al., 2024). Recently, foliar application of NPK in various ratios has become an important method for meeting the high nutrient demands of many crops, improving both nutrient uptake and use efficiency (Paikra et al., 2018). The particle size of phosphorus fertilizers greatly influences their effectiveness, with smaller particles enhancing bioavailability and agronomic performance. As Mortvedt (1992) noted, reducing particle size increases surface area, accelerating the dissolution of low-solubility fertilizers. Nanoparticles, due to their tiny size and unique properties, are ideal for phosphorus delivery, improving nutrient uptake and plant growth. Nano phosphatic fertilizers offer a promising solution for optimizing phosphorus use efficiency, minimizing losses, and boosting yields (Kumar et al., 2019). According to Rameshaiah et al. (2015), Nano fertilizers enhance efficiency by precisely releasing nutrients in the right amounts, without harming soil health or plant development. The introduction of Nano fertilizers has transformed agriculture by enabling precise nutrient delivery tailored to crop-specific needs, reducing losses and enhancing uptake (Mangaraj et al., 2018). These fertilizers, made of nutrient-encapsulating nanoparticles, represent a major advancement over conventional fertilizers, whose excessive and improper use has harmed both human health and the environment (Vaghar et al., 2020). Nano fertilizers were used in precise amounts to meet specific crop needs, reducing excess and waste. These tiny particles contained essential nutrients. Unlike traditional fertilizers, often overused and harmful to health and the environment, nano fertilizers offer a more targeted and sustainable approach (Bhanudas, 2023). Nano-DAP supplied nitrogen (N) and phosphorus (P_2O_5), key for chlorophyll, proteins, enzymes, energy transfer, and nutrient movement. It contained 8% nitrogen (80,000ppm) and 16% phosphorus (1,60,000 ppm). IFFCO's Nano-DAP, developed using nanotechnology, met nutrient demands through foliar application. Nutrients were released slowly, improving efficiency threefold and enhancing germination, growth, nitrogen metabolism, photosynthesis, protein synthesis, and antioxidant defence (Navghare et al., 2023). As soybeans are highly responsive to nitrogen and phosphorus, particularly requiring more phosphorus than other oilseed crops, there is a clear need for efficient, targeted fertilization. Therefore, a detailed field experiment was designed response of soybean through varied phosphorus levels and foliar application of Nano-DAP.

2. MATERIALS AND METHODS

2.1. Experimental site and growing conditions

The field experiment was conducted at the Main Agricultural Research Station, University of Agricultural Sciences, Dharwad, Karnataka, India, during the *kharif* July to October, 2023. The geographical coordinates: latitude 150 29' 51.2" N, longitude 740 59' 19.9" E, and at an altitude of 678 m above mean sea level. The research station comes under the Northern transition zone (Zone-8) of Karnataka, which lies between the Western hilly zone (Zone-9) and the Northern dry zone (Zone-3). The average rainfall was 803 mm, distributed in 63 rainy days. The total amount of rainfall received during the cropping period was 356 mm (19th June to 20th Oct) distributed in 23 rainy days. The mean maximum temperature recorded during the cropping period was 26.7-31.6°C, the lowest temperature during was 19.2-20.9°C. The relative humidity was observed to be highest (90.50%) during July and lower relative humidity was observed (68.00%) during October (Figure 1). The soil was black clay (Vertisol) in texture with neutral in reaction, normal in electrical conductivity (0.28 dSm^{-1}), medium in organic carbon content (0.45%), low in available nitrogen (256.32 kg ha^{-1}), medium in phosphorus (31.20 kg ha^{-1}) and high in potassium available (320.46 kg ha^{-1}).

2.2. Experimental design and layout

The experiment was laid out in a split-plot design with three replications comprising three main plots, viz. M_1-100% RDP; M_2-75% RDP; M_3-control and four subplots viz. S_1-foliar application of Nano-DAP @ 4 ml l^{-1} at 30 DAS; S_2-foliar application of Nano-DAP @ 4 ml l^{-1} at 45 DAS; S_3-foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS; S_4- no foliar application of Nano-DAP. The seeds

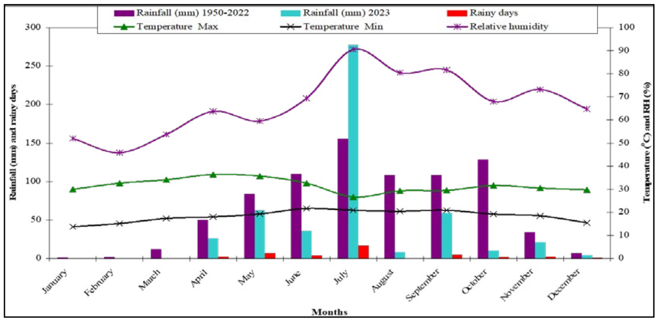

Figure 1: Monthly mean meteorological data during crop growth period (2022) and average of 72 years (1950-2022) at Main Agricultural Research Station, Dharwad

of the soybean variety DSb-34 at 80 kg ha^{-1} were used for sowing. At each spot, two seeds were dibbled up to a depth of 2.5 to 3 cm in the seed line of 5 cm within the rows and 30 cm between the rows, spacing in a plot size of 3.6 m×5 m. After the emergence of the crops, gaps in the field were filled by dibbling 2–3 seeds per hill. In order to maintain a uniform plant population and reduce competition between seedlings by leaving one healthy seedling per hill, thinning was carried out by uprooting the extra and disease-affected plants to maintain the required plant population. Farmyard manure at the recommended dose of 5 t ha^{-1} was applied uniformly and incorporated into the soil before 10 days of soybean sowing. Urea, di-ammonium phosphate (DAP) and muriate of potash (MOP) were used as sources of N, P_2O_5 and K_2O at the recommended dose (40:80:25:12.5 kg N, P_2O_5, K_2O, $ZnSO_4$ ha^{-1}) and the entire dose as a basal dose. Experimental land was kept free from weeds throughout the crop growth period. Hand weeding followed by inter-cultivation was carried out 45 and 60 days after sowing. The inter-cultivation was carried out using a cycle weeder and blade harrow. From each plot, five healthy plants were randomly selected to observe growth parameters. The observations on yield parameters were recorded at harvest. Harvesting was done manually, excluding the two border rows on each side of a plot. Then the harvested crop was left as such in the field for two days for sun drying. The produce was then taken to the threshing floor and threshed separately for each plot manually. The haulm and seeds of each plot were dried separately in the sun. after proper cleaning and drying, seeds and haulm of each net plot were weighed and yields were recorded. The observations were recorded on plant height (cm), number of branches per plant, leaf area (dm^2 plant^{-1}), leaf area index, total dry matter accumulation (g plant^{-1}), SPAD value, number of nodules per plant, nodule dry weight, root attributes and yield parameters viz. number of pods per plant, seed yield per plant, test weight (g), seed yield (kg ha^{-1}), haulm yield (kg ha^{-1}), harvest index and qualitative traits, viz. protein content (%), protein yield (kg ha^{-1}), oil content (%), oil yield (kg ha^{-1}) and nutrient uptake by plants (N, P and K). Nutrient uptake in seed and haulm was calculated by multiplying nutrient content by seed and haulm yield. Seed protein content (%): Nitrogen content in soybean seed was estimated by the Kjeldahl method and Protein content in grains is calculated by multiplying the nitrogen content by a factor of 6.25 (Tai and Young, 1974).

2.3. Statistical analysis

The experimental data obtained at different growth stages will be compiled and subjected to statistical analysis by adopting Fischer's method of analysis of variance technique. The level of significance used in 'F' test will be at 0.05%. The treatment means were compared by Duncan's Multiple Range Test (DMRT) at a 0.05 level of probability (Gomez and Gomez, 1984).

3. RESULTS AND DISCUSSION

3.1. Influence of varied phosphorus levels on growth, yield, quality and nutrient uptake of soybean

3.1.1. Growth parameters

At 30, 60 and 90 DAS, the growth parameters of soybean were significantly influenced by varied phosphorus levels. Application of 100% RDP (M_1) recorded significantly higher plant height (19.26, 38.81 and 42.15 cm), number of branches per plant (2.83, 5.89 and 6.73), total dry matter accumulation (2.57, 20.82 and 28.78 g plant^{-1}) at 30, 60 and 90 DAS, respectively, leaf area (4.44, 12.23 and 9.33 dm^2 plant^{-1}), leaf area index (1.48, 4.07 and 3.11) at 30, 60 and 80 DAS, respectively, SPAD value (31.05 and 50.10 at 30 and 50 DAS), number of nodules per plant (47.08), nodule dry weight (55.16 mg), total root length (1167 cm plant^{-1}), total root volume (3.63 cm^3 plant^{-1}), root diameter (0.69 mm plant^{-1}), total root surface area (214.15 cm^2 plant^{-1}) and total root dry weight (2240 mg plant^{-1}) at peak flowering time, which was on par with 75% RDP (M_2) as compared to control without phosphorus application (M_3) (Table 1 and 2). This may be because nitrogen, a key component of protoplasm, supports photosynthesis, boosts metabolic activity, and promotes cell division and elongation, leading to faster plant growth. Phosphorus further aids root development, leaf expansion, and cell elongation, contributing to increased plant height with fertilizer application up to an optimal level. Similar findings were reported by Rathore et al. (2010), who observed that higher fertilizer application enhances nutrient uptake, stimulating cell division and improving growth attributes. Similar findings were reported by Rabbani et al. (2023), who suggested that the application of 100% of the recommended dose of phosphorus may be optimal for achieving better growth, yield, and quality of soybean. Application of SSP

Table 1: Growth parameters of soybean at different growth stages as influenced by varied phosphorus levels and foliar application of Nano-DAP

Treatment	Plant height (cm)			No. of branches plant^{-1}			Leaf area (dm^2 plant^{-1})			Leaf area index		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	80 DAS	30 DSA	60 DSA	80 DSA
Main plot:- Varied phosphorus levels (M)												
M$_1$:100% RDP	19.26^{a}	38.81^{a}	42.15^{a}	2.83^{a}	5.89^{a}	6.73^{a}	4.44^{a}	12.23^{a}	9.33^{a}	1.48^{a}	4.07^{a}	3.11^{a}
M$_2$:75% RDP	18.43^{a}	34.65^{b}	37.38^{b}	2.56^{b}	4.91^{b}	5.94^{b}	4.23^{a}	10.63^{b}	7.77^{b}	1.41^{a}	3.56^{b}	2.59^{b}
M$_3$:Control	17.47^{b}	31.03^{c}	33.18^{c}	2.11^{c}	4.29^{c}	5.12^{c}	3.61^{b}	8.61^{c}	5.71^{c}	1.20b	2.87^{c}	1.90^{c}
S.Em.±	0.27	0.55	0.58	0.03	0.10	0.10	0.10	0.30	0.12	0.02	0.01	0.03
Sub plot:- (FA)-Foliar application of Nano-DAP (S)												
S$_1$: FA at 30 DAS	18.49^{a}	34.81^{b}	37.61^{b}	2.50^{a}	4.99^{b}	5.91^{b}	4.10^{a}	10.46^{b}	7.56^{b}	1.37^{a}	3.48^{b}	2.52^{b}
S$_2$: FA at 45 DAS	18.29^{a}	34.65^{b}	36.92^{b}	2.49^{a}	4.95^{b}	5.88^{b}	4.08^{a}	10.39^{b}	7.49^{b}	1.36^{a}	3.46^{b}	2.50^{b}
S$_3$: FA at 30 & 45 DAS	18.54^{a}	36.76^{a}	39.77^{a}	2.51^{a}	5.44^{a}	6.34^{a}	4.11^{a}	11.20^{a}	8.34^{a}	1.37^{a}	3.75^{a}	2.78^{a}
S$_4$: No FA	18.22^{a}	33.00^{c}	35.96^{c}	2.47^{a}	4.74^{c}	5.60^{c}	4.07^{a}	9.92^{c}	7.02^{c}	1.36^{a}	3.31c	2.34^{c}
S.Em.±	0.32	0.26	0.28	0.03	0.06	0.05	0.05	0.02	0.05	0.02	0.01	0.01
Interaction (M×S)												
M$_1$S$_1$	19.13^{a}	38.66^{b}	42.20^{b}	2.81^{a}	5.80^{b}	6.60^{b}	4.43^{a}	12.19^{b}	9.29^{b}	1.48^{a}	4.06^{b}	3.10^{b}
M$_1$S$_2$	19.27^{a}	38.00^{bc}	42.12^{b}	2.83^{a}	5.75^{bc}	6.56^{bc}	4.45^{a}	12.14^{b}	9.24^{b}	1.48^{a}	4.05^{b}	3.08^{b}
M$_1$S$_3$	19.33^{a}	41.87^{a}	45.80^{a}	2.86^{a}	6.50^{a}	7.43^{a}	4.46^{a}	12.98^{a}	10.08^{a}	1.49^{a}	4.33^{a}	3.36^{a}
M$_1$S$_4$	19.30^{a}	37.37^{cd}	39.92^{c}	2.82^{a}	5.52^{bc}	6.34^{cd}	4.43^{a}	11.60^{c}	8.70^{c}	1.48^{a}	3.87^{c}	2.90^{c}
M$_2$S$_1$	18.46^{a}	34.70^{e}	37.23^{de}	2.55^{a}	4.80^{d}	5.96^{e}	4.26^{a}	10.58^{d}	7.68^{d}	1.42^{a}	3.53^{d}	2.56^{d}
M$_2$S$_2$	18.43^{a}	34.50^{e}	37.00^{e}	2.54^{a}	4.75^{d}	5.92^{e}	4.20^{a}	10.52^{d}	7.62^{d}	1.40^{a}	3.51^{d}	2.54^{d}
M$_2$S$_3$	18.47^{a}	36.16^{d}	38.62^{cd}	2.58^{a}	5.43^{c}	6.26^{d}	4.23^{a}	11.41^{c}	8.64^{c}	1.41^{a}	3.85^{c}	2.88^{c}
M$_2$S$_4$	18.38^{a}	33.63^{e}	36.65^{e}	2.59^{a}	4.64^{de}	5.63^{f}	4.21^{a}	10.03^{e}	7.13^{e}	1.40^{a}	3.34^{e}	2.38^{e}
M$_3$S$_1$	17.90^{a}	31.91^{f}	33.40^{fg}	2.13^{a}	4.38^{ef}	5.18^{g}	3.62^{a}	8.60^{g}	5.70^{g}	1.21^{a}	2.87^{g}	1.90^{g}
M$_3$S$_2$	17.13^{a}	31.77^{f}	33.10^{g}	2.11^{a}	4.33^{ef}	5.16^{g}	3.60^{a}	8.52^{g}	5.62^{g}	1.20^{a}	2.84^{g}	1.87^{g}
M$_3$S$_3$	17.83^{a}	32.41^{f}	34.90^{f}	2.17^{a}	4.40^{ef}	5.32^{g}	3.65^{a}	9.21^{f}	6.31^{f}	1.22^{a}	3.07^{f}	2.10^{f}
M$_3$S$_4$	17.00^{a}	29.96^{g}	31.30^{h}	2.05^{a}	4.05^{f}	4.82^{h}	3.58^{a}	8.02^{h}	5.22^{h}	1.19^{a}	2.71^{h}	1.74^{h}
S.Em.±	0.56	0.45	0.49	0.05	0.10	0.08	0.30	0.15	0.09	0.12	0.02	0.02

*Means followed by the same alphabet (s) within a column are not differed significantly by DMRT (p=0.05); Note: RDF 40:80:25 kg of N, P_2O_5 and K_2O ha^{-1}; Recommended N and K_2O were applied to all the plots. Source of P-DAP; Dose of Nano DAP-4 ml l^{-1}

in furrow in no-till wheat soybean cropping system shows higher growth parameters of both the crops (Duart et al., 2025).

3.1.2. Yield and yield parameters

Application of 100% RDP (M$_1$) recorded significantly higher number of pods per plant (45.26), 100 seed weight (15.20 g), seed yield (15.88 g plant^{-1}), seed yield (2564 kg ha^{-1}) and haulm yield (3222 kg ha^{-1}) as compared to control without phosphorus application (M$_3$) (Table 3). Whereas the harvest index shows a non-significant difference in all the treatments. High-yielding traits were due to the optimal nutrient supply from source to sink, enhancing metabolic activity within the plant. The increased soybean yield may be attributed to improved growth parameters, both above and below ground. Application of 125% RDF resulted in higher seed yield compared to 100% RDF and the control, as reported by Manu et al. (2021). Results from the study show that there is a clear impact of raising soil test P concentration on increasing corn or soybean yield. Increasing soil test P did increase yield of corn and soybean. However, similar yields were achieved for

Table 2: Growth and root parameters of soybean at different growth stages as influenced by varied phosphorus levels and foliar application of Nano-DAP

Treatment	TDMA (g plant^{-1})			SPAD value		No. of nodules plant^{-1}	Nodule dry weight (mg)	TRL (cm plant^{-1})	TRV (cm^3 plant^{-1})	RD (mm plant^{-1})	TRSA (cm^2 plant^{-1})	TR DW (mg plant^{-1})
	30 DAS	60 DAS	90 DAS	30 DAS	50 DAS							
Main plot:- Varied phosphorus levels (M)												
M_1:100% RDP	2.57^a	20.82^a	28.78^a	31.05^a	50.10^a	47.08^a	55.16^a	1167^a	3.63^a	0.69^a	214.15^a	2240^a
M_2:75% RDP	2.39^b	17.00^b	24.91^b	29.16^b	47.54^b	40.11^b	47.20^b	887^b	2.84^b	0.64^b	170.36^b	2146^b
M_3:Control	1.87^c	13.19^c	18.47^c	25.89^c	43.12^c	26.82^c	31.59^c	624^c	1.75^c	0.49^c	115.41^c	1747^c
S.Em.±	0.04	0.31	0.35	0.20	0.15	0.27	1.01	16.80	0.07	0.02	2.98	8.20
Sub plot:- (FA)-Foliar application of nano-DAP (S)												
S_1: FA at 30 DAS	2.28^a	17.10^b	24.11^b	28.90^a	47.19^b	38.39^b	45.09^b	901^b	2.76^b	0.62^a	169.47^b	2048^b
S_2: FA at 45 DAS	2.27^a	16.98^b	23.90^b	28.71^a	46.98^b	37.81^b	44.83^b	886^b	2.75^b	0.60^a	167.22^b	2039^b
S_3: FA at 30 & 45 DAS	2.29^a	18.36^a	26.27^a	28.88^a	47.92^a	40.60^a	47.50^a	988^a	3.06^a	0.63^a	182.28^a	2087^a
S_4: No FA	2.26^a	15.58^c	22.43^c	28.32^a	45.59^c	35.20^c	41.18^c	794^c	2.38^c	0.59^a	147.59^c	2004^c
S.Em.±	0.02	0.19	0.12	0.64	0.10	0.14	0.15	8.50	0.03	0.02	1.43	4.12
Interaction (M×S)												
M_1S_1	2.57^a	20.95^b	28.73^b	31.27^a	50.30^b	47.80^b	55.92^b	1184^b	3.69^b	0.70^a	220.75^b	2246^b
M_1S_2	2.56^a	20.90^b	28.64^b	31.52^a	50.11^b	47.30^b	55.67^b	1162^b	3.68^b	0.69^a	218.35^b	2238^b
M_1S_3	2.58^a	22.85^a	30.13^a	30.89^a	51.20^a	49.20^a	57.56^a	1296^a	3.90^a	0.71^a	231.27^a	2271^a
M_1S_4	2.56^a	18.60^c	27.62^c	30.53^a	48.82^c	44.00^c	51.48^c	1025^c	3.24^c	0.68^a	186.22^c	2206^c
M_2S_1	2.39^a	17.09^d	24.91^d	28.95^a	47.94^{de}	40.17^d	47.38^d	885^d	2.84^d	0.65^a	172.42^d	2148^d
M_2S_2	2.38^a	16.90^d	24.66^d	29.65^a	47.72^e	39.47^d	46.90^d	871^d	2.82^d	0.64^a	169.77^d	2139^d
M_2S_3	2.40^a	18.20^c	26.98^c	29.22^a	48.36^{cd}	43.20^c	50.54^c	983^c	3.12^c	0.66^a	180.98^c	2191^c
M_2S_4	2.38^a	15.82^e	22.94^e	28.80^a	46.12^f	37.60^e	43.99^e	808^e	2.58^e	0.63^a	158.26^e	2106^e
M_3S_1	1.86^a	13.32^g	18.70^g	26.47^a	43.34^h	27.20^g	31.95^g	635^g	1.76^g	0.50^a	115.23^g	1750^g
M_3S_2	1.87^a	13.08^g	18.42^g	24.95^a	43.12^h	26.67^g	31.92^g	626^g	1.74^g	0.49^a	113.54^g	1741^g
M_3S_3	1.88^a	14.02^f	20.00^f	26.53^a	44.20^g	29.40^f	34.40^f	684^f	2.17^f	0.51^a	134.59^f	1798^f
M_3S_4	1.86^a	12.32^h	16.74^h	25.61^a	41.82^i	24.00^h	28.08^h	550^h	1.32^h	0.47^a	98.30^h	1701^h
S.Em.±	0.03	0.33	0.24	1.10	0.30	0.28	0.35	14.73	0.04	0.10	2.48	7.80

*Means followed by the same alphabet (s) within a column are not differed significantly by DMRT (*p*=0.05); Note: RDF 40:80:25 kg of N, P_2O_5 and K_2O ha^{-1}; Recommended N and K_2O were applied to all the plots. Source of P-DAP; Dose of Nano DAP-4 ml l^{-1}

low-testing soils when adequately fertilized compared to high-and very high-P soils, indicating that, given all factors equal, building soil test P to high concentrations does not inherently increase corn and soybean yield potential (Kaiser et al., 2025). The application of phosphorus fertilizer at 40 kg ha^{-1} significantly improved soybean productivity in Jawi, Northwest Ethiopia (Adametie et al., 2024).

3.1.3. Quality parameters

Application of 100% RDP (M_1) recorded higher oil content (18.91%), oil yield (484.85 kg ha^{-1}), protein content (37.93%) and protein yield (972.91 kg ha^{-1}) as compared to control without phosphorus application (M_3) (Table 3). This can be attributed to increased nutrient availability in the rhizosphere, which stimulates the synthesis of essential

Table 3: Yield and yield parameters, quality parameters and PUE of soybean as influenced by varied phosphorus levels and foliar application of Nano-DAP

Treatment	No. of pods plant^{-1}	100 seed weight (g)	Seed yield (g plant^{-1})	Seed yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	HI (%)	Oil content (%)	Oil yield (kg ha^{-1})	Protein content (%)	Protein yield (kg ha^{-1})	PUE (%)
Main plot:- Varied phosphorus levels (M)											
M$_1$:100% RDP	45.26^{a}	15.20^{a}	15.88^{a}	2564^{a}	3222^{a}	44.36^{a}	18.91^{a}	484.85^{a}	37.93^{a}	972.91^{a}	22.81^{a}
M$_2$:75% RDP	40.15^{b}	14.55^{b}	13.85^{b}	2272^{b}	2842^{b}	44.4^{0a}	18.76^{a}	415.79^{b}	36.75^{b}	814.64^{b}	20.59^{b}
M$_3$:Control	33.85^{c}	13.51^{c}	11.28^{c}	1695^{c}	2158^{c}	44.36^{a}	18.61^{a}	318.24^{c}	32.98^{c}	564.47^{c}	-
S.Em.±	0.60	0.17	0.12	56.30	52.30	0.72	0.28	2.13	0.08	7.70	0.39
Sub plot:- (FA)-Foliar application of nano-DAP (S)											
S$_1$: FA at 30 DAS	39.52^{b}	14.43^{ab}	13.66^{b}	2161^{b}	2756^{b}	44.66^{a}	18.77^{a}	406.13^{b}	35.97^{b}	784.28^{b}	21.63^{b}
S$_2$: FA at 45 DAS	39.45^{b}	14.36^{ab}	13.63^{b}	2157^{b}	2742^{b}	44.37^{a}	18.76^{a}	405.07^{b}	35.89^{b}	781.28^{b}	21.49^{b}
S$_3$: FA at 30 & 45 DAS	41.86^{a}	14.74^{a}	14.55^{a}	2330^{a}	2922^{a}	44.36^{a}	18.82^{a}	438.98^{a}	36.40^{a}	855.56^{a}	24.82^{a}
S$_4$: No FA	37.62^{c}	14.15^{b}	12.85^{c}	2005^{c}	2515^{c}	44.36^{a}	18.68^{a}	375.00^{c}	35.28^{c}	714.91^{c}	18.85^{c}
S.Em.±	0.25	0.14	0.10	19.20	19.00	0.60	0.12	1.00	0.10	3.13	0.68
Interaction (M×S)											
M$_1$S$_1$	45.42^{b}	15.20^{ab}	15.78^{b}	2553^{b}	3202^{b}	44.36^{a}	18.91^{a}	482.77^{b}	37.92^{b}	968.10^{b}	22.58^{bc}
M$_1$S$_2$	45.34^{b}	15.17^{ab}	15.75^{b}	2549^{b}	3197^{b}	44.36^{a}	18.90^{a}	481.76^{b}	37.89^{b}	965.82^{b}	22.51^{bc}
M$_1$S$_3$	48.16^{a}	15.38^{a}	16.98^{a}	2752^{a}	3452^{a}	44.35^{a}	18.98^{a}	522.3^{3a}	38.53^{a}	1060.35^{a}	25.99^{a}
M$_1$S$_4$	42.76^{c}	15.04^{ab}	15.02^{c}	2402^{c}	3013^{c}	44.35^{a}	18.84^{a}	452.54^{c}	37.36^{c}	897.39^{c}	20.17^{cd}
M$_2$S$_1$	40.12^{d}	14.58^{bc}	13.82^{d}	2216^{d}	2780^{d}	45.28^{a}	18.78^{a}	416.16^{d}	36.80^{d}	815.49^{d}	20.68^{bd}
M$_2$S$_2$	40.04^{d}	14.50^{bc}	13.79^{d}	2210^{d}	2772^{d}	44.37^{a}	18.76^{a}	414.66^{d}	36.77^{d}	812.74^{d}	20.47^{bd}
M$_2$S$_3$	41.92^{c}	14.99^{ab}	14.68^{c}	2369^{c}	2971^{c}	44.36^{a}	18.81^{a}	445.55^{c}	37.15^{c}	879.96^{c}	23.66^{ab}
M$_2$S$_4$	38.53^{e}	14.13^{cd}	13.12^{e}	2068^{e}	2594^{e}	44.37^{a}	18.70^{a}	386.78^{e}	36.28^{e}	750.39^{e}	17.54^{d}
M$_3$S$_1$	33.81^{g}	13.52^{de}	11.39^{g}	1715^{g}	2151^{g}	44.34^{a}	18.63^{a}	319.44^{g}	33.20^{g}	569.27^{g}	-
M$_3$S$_2$	33.76^{g}	13.41^{e}	11.34^{g}	1713^{g}	2148^{g}	44.38^{a}	18.61^{a}	318.79^{g}	33.00^{g}	565.29^{g}	-
M$_3$S$_3$	35.62^{f}	13.84^{cde}	11.98^{f}	1869^{f}	2344^{f}	44.37^{a}	18.68^{a}	349.07^{f}	33.52^{f}	626.38^{f}	-
M$_3$S$_4$	32.20^{h}	13.28^{e}	10.42^{h}	1543^{h}	1936^{h}	44.36^{a}	18.51^{a}	285.67^{h}	32.20^{h}	496.95^{h}	-
S.Em.±	0.44	0.23	0.13	33.30	33.00	1.20	0.20	2.56	0.13	9.00	0.96

*Means followed by the same alphabet (s) within a column are not differed significantly by DMRT (p=0.05); Note: RDF 40:80:25 kg of N, P_2O_5 and K_2O ha^{-1}; Recommended N and K_2O were applied to all the plots. Source of P-DAP; Dose of nano DAP-4 ml l^{-1}

amino acids like cysteine and methionine, enhancing protein production and overall plant growth. Devi et al. (2013) also reported a positive link between nutrient availability and amino acid synthesis, highlighting the role of effective nutrient management in improving plant health and productivity.

3.1.4. PUE and nutrient uptake

Phosphorus use efficiency by soybean differed significantly with varied phosphorus levels. Application of 100% RDP recorded significantly higher phosphorus use efficiency (22.81%), nitrogen uptake (191.37 kg ha^{-1}), phosphorus uptake (18.88 kg ha^{-1}) and potassium uptake (74.01 kg ha^{-1}) compared to control (Table 3 and 4). Higher nutrient use efficiency is linked to greater phosphorus availability in the soil and improved plant uptake. This enhanced uptake of nitrogen, phosphorus, and potassium results from the steady nutrient supply throughout the crop's growth, enabled by the balanced use of organic and inorganic inputs. Savita et al. (2017) results revealed that soil application of humic substances @ 5 kg ha^{-1} at sowing+foliar application of humic substances extracted from vermicompost (0.2%) along with RDF at 40 DAS resulted in significantly higher nutrient uptake of N, P, K by grain, haulm, total uptake and less available nutrient status after harvest of the crop when compared to control.

3.1.5. Nutrients available in soil

Significantly higher nitrogen available (244.40 kg ha^{-1}) and potassium available (302.28 kg ha^{-1}) in soil at harvest stage of soybean was recorded under control without phosphorus applied treatment compared to application of 100% RDP. However, significantly higher phosphorus available (26.46 kg ha^{-1}) in soil was recorded under application of 100% RDP treatment compared to the control (Table 4). It is mainly due to lower uptake of respective nutrients from respective treatment that way higher availability of the following nutrients. Prakash et al. (2023) revealed that application of 100% RDF+foliar spray of Nano DAP @ 4 ml l^{-1} at 30 and 45 DAS in soybean recorded significantly higher nitrogen, phosphorus and potassium available in soil as compared to other treatment. Soybean yields in both subsequent years responded to P rate of manure addition in a parabolic pattern with optimized P rate applied to preceding corn at 70 kg P ha^{-1}. According to Niu et al. (2025) soybean yield under swine manure application was influenced by the seed N:P ratio and varied across crop rotation years, indicating temporal changes in soil phosphorus availability with manure addition.

3.1.6. Economics

The economics of soybeans differed significantly with varying phosphorus levels. Application of 100% RDP recorded significantly higher gross returns (1,28,227 ha^{-1}), net returns (84,517 ha^{-1}), and benefit cost ratio (2.94) compared to without phosphorus applied treatment (Table 4). Mainly due to higher seed yield and haulm yield were recorded under the respective treatment. Mangaraj et al. (2018) revealed that basal application of 18 kg N, 46 kg P_2O_5, 25 kg K_2O ha^{-1}+foliar application of nitrogen @ 7 kg N ha^{-1} at initiation of flowering and foliar application of nitrogen @ 7 kg N ha^{-1} at 15 days after first foliar spray recorded higher gross monetary returns, net monetary returns and B:C ratio.

3.2. Influence of foliar application of nano-DAP on growth, yield, quality and nutrient uptake of soybean

3.2.1. Growth parameters

Growth parameters of the soybean crop did not differ significantly at 30 DAS due to foliar application of Nano-DAP. The growth parameters of soybean were significantly influenced by foliar application of Nano-DAP at 60 and 90 DAS. Foliar application of Nano-DAP @ 4 ml L^{-1} at 30 and 45 DAS (S_3) recorded significantly higher plant height (36.76 and 39.77 cm), number of branches per plant (5.44 and 6.34), total dry matter accumulation (18.36 and 26.27 g $plant^{-1}$) at 60 and 90 DAS, respectively, leaf area (11.20 and 8.34 dm^2 $plant^{-1}$), leaf area index (3.75 and 2.78) at 60 and 80 DAS, respectively, SPAD value (47.92 at 50 DAS), number of nodules per plant (40.60), nodule dry weight (47.50 mg), higher total root length (988 cm $plant^{-1}$), total root volume (3.06 cm^3 $plant^{-1}$), root diameter (0.63 mm $plant^{-1}$), total root surface area (182.28 cm^2 $plant^{-1}$) and total root dry weight (2087 mg $plant^{-1}$) at peak flowering time, as compared to no foliar application of Nano-DAP (Table 1 and 2). The enhanced growth under combined foliar application is mainly due to the direct and efficient nutrient supply to plants, promoting cell division and elongation. This increased nutrient availability likely reduced stomatal resistance, boosted CO_2 fixation, improved photosynthate transport, and stimulated meristematic activity, leading to greater plant height and branching. Additionally, foliar application supported better nodulation by rapidly supplying essential nutrients, enhancing nodule number, effectiveness, and dry weight (Salim et al., 2024). It may have also promoted root development, providing more sites for rhizobial infection and proliferation in the rhizosphere, resulting in more effective nodules. Kale et al. (2024) reported that application of RDF+foliar spray of 2% DAP at 45 DAS recorded significantly the maximum growth characters such as plant height, number of branches per plant and dry matter accumulation per plant over control.

3.2.2. Yield and yield parameters

Foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (S_3) recorded significantly higher number of pods per plant (41.86), 100 seed weight (14.74 g), seed yield (14.55 g $plant^{-1}$), seed yield (2330 kg ha^{-1}) and haulm yield (2922 kg ha^{-1}) as compared to no foliar application of Nano-DAP (Table 3). Whereas the harvest index shows a non-significant difference in all the treatments. The improvement can be attributed to enhanced yield traits, increased photosynthesis, efficient resource translocation, and improved source-sink balance. Foliar nutrient application likely boosted nutrient absorption through leaves, amplifying the effects on plant physiology and resource use, leading to higher yields and better crop performance. Application of mono ammonium phosphate with partial rate at spring timing recorded higher productivity and profitability in Illinois soybean (Nakayama et al., 2024).

3.2.3. Quality parameters

Foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (S_3) recorded higher oil content (18.82%), oil yield (438.98 kg ha^{-1}), protein content (3640%) and protein yield (855.56 kg ha^{-1}) as compared to without foliar application of

Nano-DAP (Table 3). The enhanced synthesis of essential amino acids like cysteine and methionine can be attributed to improved nutrient availability in the rhizosphere, which stimulated key metabolic pathways. Efficient nutrient uptake and utilization likely boosted amino acid production. Devi et al. (2013) similarly reported a positive correlation between nutrient availability and amino acid synthesis, highlighting the importance of optimal nutrient management for maximizing plant growth and productivity. Rabbani et al. (2023) revealed that significantly higher numbers of pods, plant^{-1}, 100-seed weight and seed yield was observed with the application of 100% of RD of phosphorus.

3.2.4. PUE and nutrient uptake

Phosphorus use efficiency by soybean differed significantly to varied foliar application of Nano-DAP. Foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (S$_3$) recorded significantly higher phosphorus use efficiency (24.82%), nitrogen uptake (170.84 kg ha^{-1}), phosphorus uptake (16.39 kg ha^{-1}) and potassium uptake (64.77 kg ha^{-1}) compared to no foliar application (Table 3 and 4). It is mainly due to nutrient uptake by soybeans is a function of better root

Table 4: Nutrient uptake, nutrient available in soil and economics of soybean as influenced by varied phosphorus levels and foliar application of nano-DAP

Treatment	Nutrient uptake (kg ha^{-1})			Available nutrients in soil			Cost of cultivation	Gross returns	Net returns	B:C ratio
	N	P	K	N	P	K	(₹ ha^{-1})			
Main plot:- Varied phosphorus levels (M)										
M$_1$:100% RDP	191.37^{a}	18.88^{a}	74.01^{a}	221.42^{b}	26.46^{a}	282.36^{c}	43,544	1,28,227^{a}	84,517^{a}	2.94^{a}
M$_2$:75% RDP	161.42^{b}	16.19^{b}	61.27^{b}	228.58^{b}	24.10^{b}	291.04^{b}	42,739	1,13,499^{b}	70,590^{b}	2.66^{b}
M$_3$:Control	124.10^{c}	10.81^{c}	45.72^{c}	244.40^{a}	21.35^{c}	302.28^{a}	40,380	86,645^{c}	45,839^{c}	2.14^{c}
SEm±	0.80	0.11	0.40	2.79	0.19	1.28	-	1206.11	1203.05	0.013
Sub plot:- (FA)-Foliar application of Nano-DAP (S)										
S$_1$: FA at 30 DAS	159.10^{b}	15.31^{b}	60.42^{b}	231.22^{b}	23.91^{b}	291.06^{b}	42,340	1,08,078^{b}	65,738^{b}	2.55^{c}
S$_2$: FA at 45 DAS	158.36^{b}	15.26^{b}	60.02^{b}	232.56^{b}	24.10^{b}	292.93^{b}	42,387	1,07,887^{b}	65,500^{b}	2.55^{c}
S$_3$: FA at 30 & 45 DAS	170.84^{a}	16.39^{a}	64.77^{a}	227.00^{c}	23.10^{c}	287.94^{c}	44,992	1,16,505^{a}	71,513^{a}	2.59^{a}
S$_4$: No FA	147.55^{c}	14.22^{c}	56.13^{c}	235.11^{a}	24.77^{a}	295.64^{a}	39,185	1,00,267^{c}	61,082^{c}	2.56^{b}
SEm±	0.40	0.03	0.12	0.54	0.10	0.61	-	481.80	483.71	0.005
Interaction (M×S)										
M$_1$S$_1$	190.53^{b}	18.79^{b}	73.76^{b}	221.00^{h}	26.53^{b}	283.50^{g}	43,744	1,27,667^{b}	83,923^{b}	2.92^{b}
M$_1$S$_2$	189.98^{b}	18.76^{b}	73.10^{c}	223.02^{gh}	26.70^{b}	282.71^{g}	43,744	1,27,467^{b}	83,723^{b}	2.91^{b}
M$_1$S$_3$	205.05^{a}	20.20^{a}	79.25^{a}	216.67^{i}	25.20^{c}	277.51^{h}	46,144	1,37,578^{a}	91,434^{a}	2.98^{a}
M$_1$S$_4$	179.92^{c}	17.79^{c}	69.91^{d}	225.14^{g}	27.40^{a}	285.70^{fg}	40,544	1,20,197^{c}	79,653^{c}	2.96^{a}
M$_2$S$_1$	161.66^{e}	16.22^{e}	61.39^{f}	228.32^{ef}	24.00^{ef}	290.94^{e}	42,840	1,10,963^{d}	68,123^{e}	2.59^{cd}
M$_2$S$_2$	160.83^{e}	16.15^{e}	61.13^{f}	229.11^{e}	24.20^{de}	291.17^{e}	42,840	1,10,638^{d}	67,798^{e}	2.58^{cd}
M$_2$S$_3$	171.89^{d}	17.19^{d}	64.99^{e}	225.32^{fg}	23.60^{f}	287.77^{f}	45,240	1,18,490^{c}	73,250^{d}	2.62^{c}
M$_2$S$_4$	151.29^{f}	15.20^{f}	57.58^{g}	232.16^{d}	24.60^{d}	294.29^{d}	39,640	1,03,611^{e}	63,971^{f}	2.61^{c}
M$_3$S$_1$	125.10^{h}	10.92^{h}	46.11^{i}	244.65^{b}	21.20^{h}	301.75^{b}	40,175	85,854^{g}	45,679^{h}	2.14^{e}
M$_3$S$_2$	124.28^{h}	10.87^{h}	45.84^{i}	245.69^{ab}	21.40^{h}	301.92^{b}	40,175	85,701^{g}	45,526^{h}	2.13^{e}
M$_3$S$_3$	135.59^{g}	11.79^{g}	50.06^{h}	239.13^{c}	20.50^{i}	298.53^{c}	43,375	93,444^{f}	50,069^{g}	2.15^{e}
M$_3$S$_4$	111.44^{i}	9.68^{i}	40.88^{j}	248.32^{a}	22.30^{g}	306.93^{a}	36,975	77,135^{h}	40,160^{i}	2.09^{f}
SEm±	0.98	0.05	0.21	0.91	0.18	1.05	-	834.50	832.70	0.01
Initial values				256.32	31.20	320.46		-		

*Means followed by the same alphabet (s) within a column are not differed significantly by DMRT (p=0.05); Note: RDF 40:80:25 kg of N, P_2O_5 and K_2O ha^{-1}; Recommended N and K_2O were applied to all the plots. Source of P-DAP; Dose of nano DAP-4 ml l^{-1}

growth and development, better translocation of resources and also partly due to an increase in nutrient uptake. Paikra et al. (2018) revealed that application of RDF+spray of DAP @ 2% at pod initiation stage of soybean crop growth resulted in significantly higher uptake of nutrients N, P, K and also a positive effect on micronutrients compared to the application of RDF+water spray at the pod initiation stage and RDF only.

3.2.5. Nutrients available in soil

Significantly higher nitrogen available (235.11 kg ha^{-1}), Phosphorus available (24.77 kg ha^{-1}) and potassium available (295.64 kg ha^{-1}) in soil at the harvest stage of soybean was recorded under without foliar application of Nano-DAP as compared to foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (S_3) (Table 4). It is mainly due to lower uptake of respective nutrients from respective treatment that way higher availability of the following nutrients. Mala et al. (2017) examined the effect of Nano slow-release fertilizers on soil fertility. Their results showed a significant increase in soil NPK levels, ensuring nutrient availability for subsequent crops. The rise in nitrogen was due to both the slow-release mechanism and nitrogen fixation by Rhizobium in Vigna radiata. Increased phosphorus and potassium levels were attributed to the solubilization of rock phosphate and rock potash.

3.2.6. Economics

The economics of soybean differed significantly to the varied foliar application of Nano-DAP. Foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (S_3) recorded significantly higher gross returns (1,16,505 ha^{-1}), net returns (71,513 ha^{-1}) and benefit cost ratio (2.59) compared to without foliar application of Nano-DAP (Table 4). Prabhu et al. (2023) revealed that an increase in the basal and foliar fertilizer application, i.e., RDF+DAP @ 2%+Urea @ 2% at 30 DAS and DAP @ 2%+Urea @ 2% at 50 DAS had significantly increased the gross returns, net returns and B-C ratio over control.

3.3. Combined influence of varied phosphorus levels and foliar application of nano-DAP on growth, yield, quality and nutrient uptake of soybean

Application of 100% RDP+foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (M_1S_3) recorded significantly higher seed yield (2752 kg ha^{-1}) and haulm yield (3452 kg ha^{-1}), followed by application of 100% RDP+foliar application of Nano-DAP @ 4 ml l^{-1} at 30 DAS (M_1S_1). The increased seed yield and haulm yield were due to improved yield attributes, viz., number of pods per plant (48.16), 100 seed weight (15.38 g), seed yield (16.98 g $plant^{-1}$). Increase in yield and yield attributes was due to higher growth in term of plant height (41.87 and 45.80 cm), number of branches per plant (6.50 and 7.43), total dry matter accumulation (22.85 and 30.13 g $plant^{-1}$) at 60 and 90 DAS, respectively, leaf area (12.98 and 10.08 dm^2 $plant^{-1}$), leaf area index (4.33 and 3.36) at 60 and 80 DAS, respectively, SPAD value (51.20 and 47.92 at 30 and 50 DAS), number of nodules $plant^{-1}$ (49.20) and nodule dry weight (57.56 mg) at peak flowering stage. Increase in growth parameters of soybean was due to higher root growth in terms of total root length (1296 cm $plant^{-1}$), total root volume (3.90 cm^3 $plant^{-1}$), root diameter (0.71 mm $plant^{-1}$), total root surface area (231.27 cm^2 $plant^{-1}$) and total root dry weight (2271 mg $plant^{-1}$). Growth parameters of the soybean crop did not differ significantly at 30 DAS due to the interaction effect of varied phosphorus levels and foliar application of Nano-DAP (Table 1, 2 and 3). Whereas, significantly lower growth parameters of soybean were recorded under without phosphorus applied with no foliar application of Nano-DAP treatment. El-Azizy et al. (2021) observed a significant increase in haulm yield and seed yield with the application of 250 and 500 ppm of Nano phosphorus fertilizer per fed, respectively, compared to the control treatment in broad bean. According to Divya et al. (2024) the application of 100% RDF along with foliar spray of 4% DAP resulted in the highest growth (plant height, number of branches, number of functional leaves, mean leaf area and plant dry matter) and yield (seed yield and straw yield) of soybean compared to all other treatments, though it was on par with 4% Nano DAP and 2% DAP alongside 100% RDF. Daware et al. (2024) reported that applying 75% of the recommended dose of conventional urea and DAP as basal, combined with seed priming using Nano-DAP and foliar sprays of 25% Nano-urea and Nano-DAP at 20 and 40 DAS, significantly enhanced the growth and yield parameters and root biomass of soybean.

A significant positive correlation was observed among yield and yield-contributing parameters in soybean by application of varied phosphorus levels and foliar spray of Nano-DAP (Table 5).

3.3.1. Quality parameters

No significant difference in seed oil content was noticed due to the interactive influence of varied phosphorus levels and foliar applications. But higher oil content was noticed in (M_1S_3) (18.98%). However, significant difference among oil yield, seed protein content and seed protein yield were noticed. Likewise, application of 100% RDP+foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (M_1S_3) recorded significantly higher oil yield (522.33 kg ha^{-1}), seed protein content (38.53%) and seed protein yield (1060.35 kg ha^{-1}) over other treatments (Table 3). Shaikh et al. (2024) suggested that application of 100% recommended

Table 5: Correlation coefficient between yield and yield parameters of soybean as influenced by varied phosphorus levels and foliar application of Nano-DAP

Yield parameters	No. of pods plant^{-1}	100-seed weight (g)	Seed yield (g plant^{-1})	Seed yield kg ha^{-1}	Haulm yield kg ha^{-1}
No. of pods plant^{-1}	1				
100-seed weight (g)	0.983**	1			
Seed yield (g plant^{-1})	0.998**	0.986**	1		
Seed yield (kg ha^{-1})	0.997**	0.990**	0.999**	1	
Haulm yield (kg ha^{-1})	0.997**	0.990**	0.999**	1.000**	1

**Significant at (p=0.05); A significant positive correlation was observed among yield and yield-contributing parameters in soybean by application of varied phosphorus levels and foliar spray of Nano-DAP

dose of Nano-DAP (RDNP) with seed treatment and foliar spray at 0.4% at 30 days after sowing enhanced protein content, protein yield, oil content and oil yield as compared to control. Yacoub et al. (2020) reported that application of 50% recommended phosphorus, combined with foliar spraying of neutral rock P nanoparticles and $ZnSO_4$ or ZnO Nano, resulted in significantly higher protein content, protein yield, oil content and oil yield in soybean.

3.3.2. PUE, nutrient uptake and nutrients available in soil

Significantly higher phosphorus use efficiency (25.99%), nitrogen uptake (205.05 kg ha^{-1}), phosphorus uptake (20.20 kg ha^{-1}) and potassium uptake (79.25 kg ha^{-1}) by soybean crop were recorded in the treatment of 100% RDP+foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS (M_1S_3). Whereas, in the same treatment (M_1S_3) reverse tread were noticed on available nitrogen and potassium in soil at the harvest stage of soybean. However, higher phosphorus availability in soil at the harvest stage of the soybean crop were recorded under application of 100% RDP+no foliar application of Nano-DAP (Table 3 and 4). Veeramallu et al. (2024) concluded that 100% RDF+Foliar Spray of Nano-DAP (30 DAS) showed positive response over other treatments significantly increased in content and uptake of nitrogen, phosphorus, potassium and sulphur. Burhan and Hassan (2019), noted that foliar application of liquid Nano NPK fertilizer at a 15% concentration led to the highest uptake of NPK by the plant, underscoring the benefits of Nano fertilizers in improving nutrient use efficiency of the crop and promoting plant growth.

3.3.3. Economics

Among the interaction effects, (M_1S_3) 100% RDP+foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS recorded significantly higher gross returns (₹ 1,37,578 ha^{-1}), net returns (₹ 91,434 ha^{-1}) and B:C ratio (2.98) over other treatments. However, B:C ratio is on par with (M_1S_4) (2.96) (Table 4). This finding is in direct correlation with the increased seed yield, which ultimately resulted in higher returns, thereby establishing a positive relationship between the two. The enhanced seed yield, facilitated by the higher uptake of nutrients and utilization, led to improved soybean productivity and, subsequently, higher economic returns. Paikra et al. (2018) conducted a field experiment to evaluate the effect of foliar nutrition on the uptake of nutrients and economics of soybean. The results revealed that application of RDF+spray of DAP @ 2% at the pod initiation stage of crop growth resulted in higher gross returns, net returns and B:C ratio.

4. CONCLUSION

Application of 100% RDP along with foliar application of Nano-DAP @ 4 ml l^{-1} at 30 and 45 DAS enhanced growth, improves in soybean seed oil and protein content, better root development, seed yield (43.93%) and resulted higher net returns (₹ 91,434 ha^{-1}). Further foliar application of Nano-DAP at 30 and 45 days after sowing with 100% RDF was most effective for obtaining better plant growth, root development, productivity, quality improvement, nutrients uptake and economic returns of soybean under rainfed conditions.

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