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RESEARCH PAPER

Assessing the growth and yield responses of rainfed pigeonpea (*Cajanus cajan* (L.) Millsp.) to nano-DAP fertilizer application

R. SACHIN[1], *S. B. PATIL[1], G. S.YADAHALLI[1], R. A. NANDAGAVI[1] AND G. Y. VIDYAVATHI[2]

[1]Department of Agronomy, [2]Department of Soil Science and Agril. Chemistry
College of Agriculture, Vijayapura - 586 101
University of Agricultural Sciences, Dharwad - 580 005, India
*E-mail: patilsb13617@uasd.in

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Abstract: A field experiment was conducted during *kharif* 2022 at the College of Agriculture, Vijayapura, in a split-plot design with two control plots. The main plots consist of basal application of N and P levels, *viz*., 100%, 75%, 50%, 25% and 0%, and subplots consist of foliar application of nano-DAP @ 2 ml, 4 ml and 6 ml L^{-1} and the treatment combinations were compared with a recommended package of practice (RPP) and absolute control. The results indicated that the basal application of 100% N and P recorded significantly higher growth, yield and economics than lower N and P levels. Among the foliar applications tested, spraying nano-DAP @ 6 ml L^{-1} resulted in significantly superior growth, yield and economic outcomes, followed by the application of nano-DAP @ 4 ml L^{-1}. Among the interactions examined, the treatment receiving 100% N and P, along with the foliar application of nano-DAP @ 6 ml L^{-1} demonstrated significantly superior growth attributes. Specifically, it exhibited a plant height of 177.5 cm, 36.10 branches per plant, and a total dry matter production of 252.2 g per plant. Additionally, this interaction treatment demonstrated better yield attributes, including more pods $plant^{-1}$ (181.79) and seed weight $plant^{-1}$ (74.43 g). Moreover, it produced significantly higher seed yield (1883 kg ha^{-1}) and stalk yield (5138 kg ha^{-1}) and maximum net returns (₹ 87329 ha^{-1}) and a benefit-cost ratio (3.36) compared to other treatment combinations. However, the treatment receiving 75% N and P, coupled with nano-DAP spraying both @ 4 and 6 ml L^{-1}, noticed comparable outcomes in terms of seed yield (1712 kg ha^{-1}), stalk yield (4768 kg ha^{-1}), net returns (₹ 79637 ha^{-1}) and a benefit-cost ratio (3.39) with RPP. The study concludes that employing a basal application of 100% N and P coupled with foliar application of nano-DAP @ 4 and 6 ml L^{-1} enhances the growth, yield, and net returns of pigeonpea in contrast to RPP.

Key words: Economics, N P levels, Nanofertilizer, Recommended package of practice

Introduction

Pigeonpea [*Cajanus cajan* (L.) Millsp] is a legume plant that belongs to the family Fabaceae and is native to Africa. It is grown predominantly for its edible seeds for food, feed, fuel, and medicine. Tender green seeds are used as vegetables, crushed seeds as animal feed, green leaves as fodder, and the stem is used as fuel wood and primarily consumed as a split pulse known as 'dal'. In India, pigeonpea production reached 4.22 million tonnes, cultivated across 4.90 million hectares with a productivity of 861 kg ha^{-1}. The major pigeonpea-growing states include Maharashtra, which accounts for 27.73% of the total production, followed by Karnataka (19.97%) and Madhya Pradesh (14.60%). Karnataka occupies an area of 1.63 million hectares with a production of 1.23 million tonnes and an average productivity of 759 kg ha^{-1} (Indiastat, 2022). It is commonly cultivated on marginal and sub-marginal soils, often intercropped with cereals such as sorghum, pearl millet, foxtail millet, and other pulses such as cowpea, soybean, urd bean, mung bean, and so on. Farmers have been cultivating pigeonpea as a monocrop in specific places, with the crop gaining popularity, particularly in districts such as Kalaburagi, Raichur, Bidar, and Vijayapura. This has led to North Karnataka being known as the "Pigeonpea Bowl" due to its prominence in pigeonpea cultivation.

Pigeonpea, being a leguminous crop, has the ability to fix atmospheric nitrogen (N) up to 120-170 kg ha^{-1}) via rhizobium nodulation, and its deep roots facilitate efficient moisture and nutrient uptake, rendering it suitable for rainfed areas as drought tolerant crop. While it's N-fixing, an initial 15-25 kg N ha^{-1} dose is often recommended. N plays a vital role in chlorophyll and enzyme formation, essential for physiological processes (Hellal and Abdelhamid *et al*., 2013). Phosphorus (P), also crucial for seed germination, cell division, and energy transformation, is the second most vital nutrient after N. Proper nutrient management is critical to pigeonpea's optimal growth and development. The research on pigeonpea nutrition management in India's drylands faces several critical gaps. Firstly, there is insufficient understanding of the specific nutrient requirements essential for pigeonpea during key growth stages, particularly at sowing and reproductive phases. This knowledge gap hinders the development of precise nutrient management strategies tailored to optimize pigeonpea yields. Secondly, imbalanced nutrient application practices prevail, often leading to suboptimal nutrient uptake and utilization by the crop. Additionally, the impact of moisture deficits on nutrient availability and uptake efficiency remains inadequately studied, despite being a significant challenge in dryland conditions. Addressing these challenges necessitates integrating foliar application of macro- and micronutrients. This method supplements conventional soil application techniques, ensuring a balanced and sustained nutrient supply throughout the crop's growth stages, thereby enhancing grain yields effectively.

The foliar application with limiting nutrients corrects the nutrient requirement but selecting more efficient nutrients that improves use efficiency with high yields. The nanofertilizers (NFs) might be a solution for increasing use efficiency while feeding crops with required nutrients and reducing the environmental impact of conventional fertilizers (Milani *et al.*, 2012; Sabir *et al.*, 2020). NFs are gaining prominence as highly valuable nanomaterials due to their small size and unique physicochemical properties (Salam *et al.*, 2022; Selim *et al.*, 2020). However, there is need to be more comprehensive studies assessing the effects of NFs applications on plant growth and yields, particularly those supplying N and P nutrients to the plant. The nano-DAP stands out as a NFs available in the market that contains both N and P, and it is recommended for foliar application. Additionally, limited studies are exploring the impact of applying nano-DAP alone or in combination with conventional fertilizers on crop growth, yield, and economic outcomes in field conditions (Kah *et al.*, 2018; Mullen, 2019). Keeping these facts in view, the present study was planned to investigate the potential positive effect of nano-DAP on pigeonpea growth and yield in field conditions.

Material and methods

A field experiment was conducted during the *kharif* season of 2022 at the College of Agriculture, Vijayapura, Karnataka on vertisols having an alkaline reaction (pH 8.03), low salinity (0.33 dSm^{-1}), medium organic carbon (0.66%), low in available nitrogen (183.32 kg N ha^{-1}), medium in available phosphorus (31.20 kg P_2O_5 ha^{-1}), and high in available potassium (416.00 kg K_2O ha^{-1}). The experimental site was situated at a latitude of 16^0 45' 51" North and a longitude of 75^0 44' 46" East, with an altitude of 593.8 meters above mean sea level, located in the Northern Dry Zone of Karnataka (Zone 3). During the experimental year (January to December 2022), a total rainfall of 793.2 mm was received across 52 rainy days as against the normal rainfall of 594.4 mm occurring over 38 rainy days. The highest rainfall of 171.7 mm was received in August, followed by October (130.9 mm). Notably, during the cropping period from July to December 2022, the total rainfall received 540 mm over 38 rainy days.

The experiment was laid out in a split-plot design with two separate control plots. The main plots consist of basal application of N and P levels, *viz*., 100%, 75%, 50%, 25% and 0% N and P, and subplots consist of foliar application of nano-DAP @ 2 ml, 4 ml and 6 ml L^1 and the combinations were compared with a recommended package of practice (RPP) and absolute control. The land was ploughed once after the harvest of the previous crop, followed by two harrowings. After sowing, the land was prepared to a fine seedbed, and the plots were laid out. The variety TS-3R was used in the study. The urea and diammonium phosphate (DAP) fertilizer was applied as per the treatment. The RPP treatment includes basal the application of 25:50:0 kg N, P_2O_5 and K_2O + 15 kg $ZnSO_4.7H_2O$ ha^{-1} and seed treatment with PSB (200 g kg^{-1}seed) and *Rhizobium* (200 g kg^{-1} seed)] were common all treatments except recommended N and P levels as per treatment and no fertilizers were applied to absolute control plot. The crop was sown on July 11, 2022, with a spacing of 90 cm between rows and 30 cm between plants within each row. Due to the incidence of pod borer [*Helicoverpa armigera* (Hubner)] and leaf webber [*Grapholita critica* (Meyr.)], sprays of Emamectin benzoate 5% SG @ 0.5 g L^{-1} of water were taken during the secondary branching, flower initiation and pod formation stage. Harvesting was done on January 12, 2023, at the physiological maturity of the crop when pods exhibited maturity symptoms. According to the treatments, the entire plot area was harvested by cutting the plants down to ground level. Once harvested, the produce was dried and weighed before threshing to determine the pod weight per plot. Threshing was carried out manually, followed by winnowing and cleaning to separate the seeds from the haulm.

Five plants were randomly selected in each treatment in the net plot area and labelled with tags to record various growth and yield parameters. Periodic biometric observations were taken in these plants at 30, 60, 90, 120 days after sowing (DAS) and harvest. The plant height was measured from the ground level to the tip of the main shoot. The total number of branches in each plant was counted from five randomly selected plants, the mean value for each treatment was determined, and total dry matter production (TDMP) in each plant was weighed from five randomly selected plants in net plots. The yield attributes and yield were recorded from the net plots, and seed yield was converted to a hectare basis in kilograms. The harvest index (HI) was determined by dividing the economic yield by the biological yield (Donald, 1962).

The economics analysis of each treatment was calculated with prevailing market prices from the corresponding year (in 2023). The yield was further computed for gross and net returns as well the benefit-cost ratio (BCR) to assess the profitability of pigeonpea production. The BCR was worked out by dividing the gross returns by the total cost of cultivation of respective treatments. The data collected from the experiment at different growth stages and harvest were subjected to statistical analysis as described by Gomez and Gomez (1984). The significance level for the 'F' and 't' tests was P=0.05. Critical Difference (CD) values were calculated at 5 percent probability level if the F test was significant. The correlation coefficient was worked out among the seed and stalk yield, growth attributes and yield attributes using R studio.

Results and discussion

Effect of basal application of nitrogen and phosphorus levels

Lowering the levels of nitrogen (N) and phosphorus (P) in basal application led to a significantly decrease growth attributes like plant height, total number of branches, total dry matter production (TDMP), and leaf area per plant, as indicated in Table 1. The treatment that received a basal application of 100% N and P exhibited significantly greater plant height (174.4 cm), total number of branches (34.92), TDMP (248.7 g $plant^{-1}$) at harvest, and leaf area (101.99 $dm^2 plant^{-1}$) at 90 DAS. The values decreased to 8.54, 8.71, 8.12 and 8.61% in the treatment that received 75% N and P levels, respectively. The significant increase of plant height and TDMP observed in treating 100% N and P levels might be attributed to the synergistic effects of these nutrients. N and P play a crucial role in promoting leaf

Table 1. Growth attributes of pigeonpea as influenced by nutrient levels and nano-DAP.

Treatments	Plant height (cm) at harvest	No. of branches at harvest	TDMP (g) at harvest	Leaf area at 90 DAS (dm^2 plant^{-1})
Nutrient levels of N and P (N)				
N_1: 100% N and P	174.4	34.92	248.7	101.99
N_2: 75% N and P	159.5	31.88	228.5	93.21
N_3: 50% N and P	148.3	28.90	194.2	77.05
N_4: 25% N and P	130.7	23.90	155.1	65.50
N_5: 0% N and P	121.0	18.65	118.4	52.05
S.Em±	4.1	0.77	3.46	2.09
C.D. (p = 0.05)	13.4	2.52	11.3	6.83
Foliar application of nano-DAP (F)				
F_1: Nano-DAP @ 2 ml L^{-1}	142.3	26.12	177.1	73.04
F_2: Nano-DAP @ 4 ml L^{-1}	148.1	27.99	193.0	79.41
F_3: Nano-DAP @ 6 ml L^{-1}	149.9	28.83	196.8	81.44
S.Em±	0.6	0.19	1.29	0.72
C.D. (p = 0.05)	1.6	0.55	3.81	2.11
Interactions (N×F)				
N_1F_1	171.4	33.88	244.2	99.69
N_1F_2	174.4	34.78	249.8	102.59
N_1F_3	177.5	36.10	252.2	103.69
N_2F_1	152.9	30.77	216.3	91.00
N_2F_2	161.6	31.70	229.1	92.65
N_2F_3	164.0	33.16	236.2	95.98
N_3F_1	145.4	27.54	176.1	72.36
N_3F_2	149.1	29.47	199.8	78.37
N_3F_3	150.3	29.69	206.6	80.43
N_4F_1	127.9	21.16	140.5	59.13
N_4F_2	131.5	24.96	159.9	68.25
N_4F_3	132.8	25.57	164.8	69.14
N_5F_1	113.7	17.26	108.5	43.01
N_5F_2	124.1	19.05	122.6	55.18
N_5F_3	125.1	19.63	124.1	57.96
S.Em±	4.2	0.85	4.19	2.47
C.D. (p = 0.05)	13.7	2.71	13.25	7.84
Control (C)				
C_1: RPP	167.1	33.56	241.5	97.90
C_2: Absolute control	105.3	15.23	101.3	39.34
S.Em±	4.4	0.75	4.92	2.62
C.D. (p = 0.05)	12.8	2.17	14.18	7.54

RPP: Recommended package of practice; TDMP: Total dry matter production

and stem growth by facilitating the formation of essential compounds such as proteins and chlorophyll. Further, they promote cellular processes, photosynthesis efficiency, and nutrient uptake. These combined effects ultimately resulted in increased plant height and dry matter accumulation (Kavitha *et al.,* 2019). Several studies have highlighted the significant effect of higher doses of N and P fertilizer application on dry matter accumulation in different parts and TDMP (Xu *et al*., 2021; Sapkota *et al*., 2017; Jaishankar and Manivannan., 2018).

The findings of the present study are in alignment with those of Kavitha *et al.* (2019), who noticed in vegetable cowpea that the application of 125% improves both growth and yield attributes compared to 100% recommended dose of fertilizer (RDF).

Yield attributes, including the number of pods plant^{-1}, seed weight plant^{-1}, and number of seeds pod^{-1} exhibited significant increases with the basal application of different levels of N and P. Still, the test weight was non-significant (Table 2). Dhaka *et al.* (2020) observed that among different fertility levels in pigeonpea, the application of 40 kg N + 40 kg P_2O_5 ha^{-1} resulted in significantly improved yield attributes, yielding a remarkable 39.7% higher seed yield than the control. In the present study, the treatment consisting of 100% N and P recorded significantly higher values for the number of pods plant^{-1} (178.22) and seed weight per plant (72.20 g), followed by the treatment with 75% N and P (165.76 and 64.20 g, respectively). The increase in yield attributes due to N and P is indispensable for boosting healthy vegetative growth and optimal grain development in pigeonpea crops. These nutrients contribute significantly to the plant's metabolic processes, chlorophyll synthesis, energy production, and root establishment (Onasanya *et al*., 2009).

The basal application of N and P levels significantly influenced the seed and stalk yield of pigeonpea (Table 2). The treatment receiving basal nutrient levels of 100% N and P exhibited a considerably higher seed and stalk yield (1835 and 5028 kg ha^{-1}). A reduction of 25% from the recommended dose

Table 2. Yield attributes and yield of pigeonpea as influenced by nutrient levels and nano-DAP

Treatments	Number of pods plant^{-1}	Seed weight plant^{-1} (g)	Test weight (g)	Seed yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
Nutrient levels of N and P (N)					
N_1: 100% N and P	178.22	72.20	10.78	1835	5028
N_2: 75% N and P	165.76	64.20	10.54	1640	4565
N_3: 50% N and P	147.36	57.86	10.42	1420	4102
N_4: 25% N and P	121.21	44.26	10.19	1179	3578
N_5: 0% N and P	95.09	33.17	10.00	768	2495
S.Em±	3.74	1.13	0.22	34	96
C.D. (p = 0.05)	12.21	3.68	NS	112	313
Foliar application of nano-DAP (F)					
F_1: Nano-DAP @ 2 ml L^{-1}	135.0	50.68	10.33	1308	3806
F_2: Nano-DAP @ 4 ml L^{-1}	143.1	55.33	10.40	1380	3999
F_3: Nano-DAP @ 6 ml L^{-1}	146.6	57.01	10.43	1417	4056
S.Em±	1.20	0.46	0.15	10	31
C.D. (p = 0.05)	3.55	1.37	NS	31	93
Interactions (N×F)					
N_1F_1	174.39	69.60	10.68	1778	4896
N_1F_2	178.48	72.58	10.81	1843	5052
N_1F_3	181.79	74.43	10.85	1883	5138
N_2F_1	161.45	62.34	10.51	1579	4434
N_2F_2	166.35	64.02	10.59	1643	4576
N_2F_3	169.48	66.26	10.51	1698	4686
N_3F_1	140.14	54.80	10.41	1376	4065
N_3F_2	149.91	58.84	10.43	1434	4109
N_3F_3	152.04	59.95	10.43	1450	4132
N_4F_1	106.93	36.93	10.10	1052	3182
N_4F_2	124.25	47.10	10.13	1214	3772
N_4F_3	132.46	48.75	10.33	1272	3780
N_5F_1	91.93	29.75	10.13	755	2453
N_5F_2	92.26	34.10	10.02	767	2487
N_5F_3	93.07	35.65	10.04	780	2545
S.Em±	4.34	1.04	0.34	23	70
C.D. (p = 0.05)	13.80	3.07	NS	69	207
Control (C)					
C_1: RPP	171.55	68.26	10.84	1712	4768
C_2: Absolute control	77.01	26.42	9.73	743	2333
S.Em±	5.52	1.46	0.33	35	119
C.D. (p = 0.05)	15.91	4.20	NS	102	341

NS: Non significant; RPP: Recommended package of practice

(*i.e.*, 75% N and P) led to a 10.63% and 9.21% decrease in seed and stalk yield (1640 and 4565 kg ha^{-1}, respectively). The lower nutrient levels might have limited protein synthesis, enzymatic activity, and energy transfer, consequently slightly reducing stalk growth and yield. Further reduction and absence of N and P basal application could severely restrict protein synthesis, enzyme activity, root development, and energy transfer. These limitations could greatly hinder overall plant growth, resulting in significantly reduced stalk yield. Similarly, Monica *et al*. (2020) concluded that applying 100% RDF recorded statistically higher grain and straw yield compared to 25% RDF, as seen in 75% RDF and 50% RDF. Similar results were obtained by Kumawat *et al*. (2013), Deshbhratar *et al*. (2010), and Gayatri and Pandian (2019). Economic parameters such as gross returns, net returns, and benefit-cost ratio (BCR) exhibited an increasing trend with N and P application, reaching their maximum levels at the highest application rate (Table 3). This trend can be attributed to the increased seed and stalk yields with basal N and P levels. The value of the increased yield outweighed the cost of nutrients, thus contributing to higher net returns and BCR. In our study, the basal application of different levels of N and P had a significant effect on gross returns, net returns, and BCR. The treatment receiving the basal application of 100% N and P levels recorded ₹ 121087 ha^{-1}, ₹ 85361 ha^{-1}, and 3.39 for gross returns, net returns, and BCR, respectively. This was followed by the treatment receiving 75% N and P levels, which recorded ₹ 108238 ha^{-1}, ₹ 73342 ha^{-1}, and 3.10 for gross returns, net returns, and BCR, respectively. Similar findings were also reported by Renuka (2022).

Effect of foliar application of nano-DAP

The foliar sprays of nano-DAP significantly influenced the growth attributes (Table 1). Notably, higher plant height, total number of branches, total dry matter production (TDMP) per plant at harvest, and leaf area were observed with foliar application of nano-DAP @ 6 ml L^{-1} (149.9 cm, 28.83, 196.8 g plant^{-1} and

Table 3. Cost of cultivation, gross returns, net returns and benefit-cost ratio (BCR) of pigeonpea as influenced by nutrient levels and nano- DAP

Treatments	Cost of cultivation (₹ ha^{-1})	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	BCR
Nutrient levels of N and P (N)				
N_1: 100% N and P	35726	121087	85361	3.39
N_2: 75% N and P	34896	108238	73342	3.10
N_3: 50% N and P	34010	93735	59725	2.76
N_4: 25% N and P	33155	77836	44681	2.34
N_5: 0% N and P	32300	50659	18359	1.57
S.Em±	-	2267	2267	0.07
C.D. (p = 0.05)	-	7393	7393	0.22
Foliar application of nano-DAP (F)				
F_1: Nano-DAP @ 2 ml L^{-1}	32817	86346	53528	2.61
F_2: Nano-DAP @ 4 ml L^{-1}	34017	91087	57070	2.66
F_3: Nano-DAP @ 6 ml L^{-1}	35217	93500	58282	2.63
S.Em±	-	691	691	0.02
C.D. (p = 0.05)	-	2038	2038	NS
Interactions (N×F)				
N_1F_1	34526	117370	82844	3.40
N_1F_2	35726	121637	85911	3.40
N_1F_3	36926	124255	87329	3.36
N_2F_1	33696	104236	70540	3.09
N_2F_2	34896	108409	73513	3.11
N_2F_3	36096	112068	75972	3.10
N_3F_1	32810	90838	58028	2.77
N_3F_2	34010	94666	60656	2.78
N_3F_3	35210	95700	60490	2.72
N_4F_1	31955	69432	37477	2.17
N_4F_2	33155	80102	46947	2.42
N_4F_3	34355	83974	49619	2.44
N_5F_1	31100	49852	18752	1.60
N_5F_2	32300	50622	18322	1.57
N_5F_3	33500	51502	18002	1.54
S.Em±	-	1545	1545	0.04
C.D. (p = 0.05)	-	4557	4557	0.13
Control (C)				
C_1: RPP	33326	112963	79637	3.39
C_2: Absolute control	28830	49035	20205	1.70
S.Em±	-	2329	2329	0.07
C.D. (p = 0.05)	-	6710	6710	0.20

RPP: Recommended package of practice

81.44 dm^2 plant^{-1}, respectively) compared to nano-DAP @ 2 ml L^{-1}. This enhanced growth could potentially be attributed to the application of nanoscale nutrient increased tryptophan in meristematic cells, which triggered auxins resulting in higher plant height. Additionally, the application of nano-based nutrients, particularly N and P, has been noted to positively influence the branching development of peas and other pulse crops, as observed by Abd Alqader *et al.* (2020). Consistent with our findings, Merghany *et al.,* 2019 opined that the application of liquid nano-NPK @ 6 ml L^{-1} significantly improved the plant height, number of leaves, chlorophyll content, and fruit yield in cucumber. Similar results were also found by Islam *et al.* (2023) and Gomma *et al.* (2018).

The foliar application of nano-DAP also had a significant impact on both seed and stalk yields (Table 2). Specifically, spraying nano-DAP @ 6 ml L^{-1} produced substantially higher seed and stalk yields (1417 and 4056 kg ha^{-1}, respectively) compared to the nano-DAP @ 2 ml L^{-1} (Table 2). The higher seed yield and stalk yields can be attributed to more pods per plant (146.6), higher seed weight per plant (57.01g) and enhanced test weight (10.43 g). This might be due to nanofertilizers integrating nanoscale devices to harmonize the controlled release of N and P fertilizers, optimizing crop absorption (DeRosa *et al*., 2010). Higher concentrations of nanofertilizer lead to a larger surface area, making it easier for the leaves to absorb more nutrients when sprayed. Consequently, this leads to a greater number of pods per plant, boosting flower growth and facilitating nutrient transport during the plant's reproductive phase, as also observed by Hassan and Lehmood (2019). Additionally, Liu and Lal (2014) observed that the application of nano apatite @ 1 ml L^{-1} increased the growth rate and seed yield by 32.6 and 20.4%, respectively compared to soybeans treated with a regular P fertilizer.

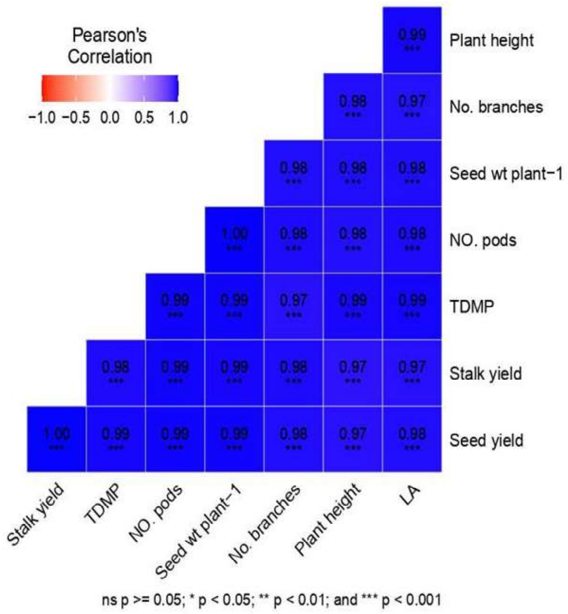

Fig. 1 Correlation matrix analysis for seed yield and stalk yield attributes and growth attributes of pigeonpea as influenced by nutrient levels and nano-DAP.

The foliar application of nano-DAP also significantly impacted gross returns, net returns, and BCR as outlined in Table 3. Specifically, the foliar spray of nano-DAP @ 6 ml L^{-1} produced significantly higher gross returns (₹ 93500 ha^{-1}) and net returns (₹ 58282 ha^{-1}). However, a higher BCR (2.66) was found with nano-DAP applied @ 4 ml L^{-1}. Nevertheless, the treatment of nano-DAP @ 4 ml L^{-1} (₹ 91087 and 57070 ha^{-1}, respectively) was statistically on par with the nano-DAP @ 6 ml L^{-1} treatment except for the BCR. This variance could be attributed to the highest seed yield achieved through foliar sprays, which consequently influenced the economic outcomes. Similar conclusions were drawn by Renuka (2022).

Interaction effect of basal application of N and P levels and foliar application of nano-DAP

The combined application of basal N and P levels with foliar nano-DAP significantly increased the growth attributes such as plant height and number of branches per plant at harvest in the pigeonpea, directly contributing to the TDMP (Table 1). Specifically, the treatment combination of 100% N and P + nano-DAP @ 6 ml L^{-1} produced significantly taller plants, more branches per plant, higher TDMP and larger leaf area (177.5 cm, 36.10, 252.2 g, 103.69 dm^2 $plant^{-1}$, respectively). Conversely, the treatment with 0% N and P + nano-DAP @ 2 ml L^{-1} resulted in decreased plant height, number of branches per plant, TDMP, and leaf area of the pigeonpea by 35.94%, 52.19%, 56.98%, and 58.52% over 100% N and P + nano-DAP @ 6 ml L^{-1} treatment. The correlation studies further these observations (Fig. 1), clearly indicating a positive and significant correlation between seed yield and plant height (r=0.972), number of branches (r=0.978), TDMP (r=0.989), and leaf area (r=0.978). Soil applied N and P fertilizers provide a steady supply of essential nutrients to support vegetative growth, resulting in increased branching. Additionally, foliar application of nano-DAP enhances P availability during the reproductive phase, facilitating flower development and ultimately leading to more TDMP, pod formation, and a better seed set. This dual approach optimizes nutrient availability throughout the plant's life cycle, from vegetative growth to reproduction. Soil applied N and P fertilizers also support early plant development, while foliar nano-DAP application fine-tunes nutrient supply during the critical flowering and seed-filling stages. These results closely conform with previous studies conducted by Ajithkumar *et al.* (2021) and Kumar *et al.* (2022).

Pigeonpea yield, resulting from various yield attributes, was significantly affected by basal application of N and P levels and foliar application of nano-DAP (Table 2). Among different treatment combinations, the maximum seed yield of 1883 kg ha^{-1} and stalk yield of 5138 kg ha^{-1} of pigeonpea was achieved with the basal application of 100% N and P, along with a foliar spray of nano-DAP @ 6 ml L^{-1}. Subsequent reduction of the recommended dose (100% N and P) by 25%, coupled with nano-DAP foliar sprays, led to a decrease in seed and stalk yields by 9.82% and 8.80%, respectively with 75% N and P + nano-DAP @ 6 ml L^{-1}. A more substantial decline of 59.90% in seed yield and 52.26% in stalk yield with no basal N and P with nano-DAP @ 2 ml L^{-1} application treatment. This indicates the necessity of optimum basal nutrient levels for better growth and development. The cumulative beneficial effect of yield attributing characters is also finally reflected in the seed yield. Like seed and stalk yield, the same treatment receiving the basal application of 100% N and P with foliar spray of nano-DAP @ 6 ml L^{-1} produced better yield attributes like the number of pods per plant (181.79) and seed weight per plant (74.43 g), which were statistically on par with the combination of 100% N and P with nano-DAP @ 4 ml L^{-1} combination. However, test weight was not significantly affected by either treatment. The correlation studies further support this view (Fig. 1), and it indicated a positive and significant correlation between seed yield and stalk weight (r=0.998), number of pods (r=0.994), and seed weight per plant (r=0.993). These results are in close conformity with prior studies by Ajithkumar *et al.* (2021), Kumar *et al.* (2022), and Saitheja *et al.* (2022), which similarly emphasized the significance of 100% recommended dose of N with nano-urea @ 4 ml L^{-1} in achieving higher number of pods per plant, seeds per pod and maximum grain yield.

The combined interactions between basal N and P and the foliar application of nano-DAP led to increased gross returns, net returns, and BCR. Specifically, the interaction treatment receiving the basal application of 100% N and P with foliar spray of nano-DAP @ 6 ml L^{-1} recorded higher gross returns (₹ 124255 ha^{-1}), net returns (₹ 87329 ha^{-1}), but the highest BCR (3.40) was recorded in 100% N and P along with nano-DAP @ 4 ml L^{-1} and 2 ml L^{-1}. This discrepancy in BCR values is attributed to the higher cost of cultivation with the use of nano-DAP @ 6 ml L^{-1} (Table 3). These results conform with Renuka (2022) and Kumar *et al.* (2022), further reinforcing the economic benefits of optimizing N and P levels in conjunction with appropriate nano-DAP application rates.

Comparison between treatment combinations with the recommended package of practice and absolute control

A significant variation in plant height, number of branches, TDMP, number of pods per plant, leaf area, seed weight per plant, seed yield, and stalk yield was also found by comparing the treatment combinations with the recommended package of practices (RPP) and absolute control (AB). The treatment combination of 100% N and P + nano-DAP @ 6 ml L^{-1} recorded a significantly higher seed and stalk yield (1883 and 5138 kg ha^{-1}, respectively). When RPP was compared with treatment combinations, the RPP (1712 and 4768 kg ha^{-1}, respectively) was statistically on par with those obtained with100% N and P + nano-DAP @ 2 ml L^{-1}, 75% N and P + nano-DAP @ 6 ml L^{-1} and 75% N and P + nano-DAP @ 4 ml L^{-1}. However, significantly lower seed and stalk yield (743 and 2333 kg ha^{-1}) was recorded with the absolute control. In comparison with economics, RPP was similar gross returns (₹ 112963) and net returns (₹ 79637) with treatment combination of 100% N and P along with nano-DAP @ 2 ml L^{-1}, 75% N and P along with nano-DAP @ 6 ml L^{-1} and 75% N and P along with nano-DAP @ 4 ml L^{-1}. The maximum BCR was recorded with RPP (3.39) compared to the treatment of 100% N and P along with nano-DAP @ 6 ml L^{-1}. Still, gross returns and net returns were lower than the best-performing treatments. This difference could be attributed to the higher grain yield of pigeonpea and the reduction in the cost of cultivation in the treatment receiving RPP. These results conform with Renuka (2022) and Kumar *et al.* (2022), further validating the efficacy of specific treatment combinations in enhancing pigeonpea yield and economic returns.

Conclusion

Considering the basal application of 100% nitrogen (N) and phosphorus (P), along with the foliar application of nano-DAP at 4 and 6 ml L^{-1}, resulted in higher yields and net returns. However, the associated costs exceeded the recommended package of practice (RPP). For improved nutrient management and profitability, an alternative approach could be adopting 75% of the recommended basal N and P application rates, complemented with foliar sprays of nano-DAP at 6 ml L^{-1}. This strategy not only enhances growth and yield but also achieves a higher benefit-cost ratio (BCR). It allows for a significant reduction of 25% in nitrogen and phosphorus use, contributing to cost savings while maintaining agricultural productivity. Thus, recommending 75% N and P basal application with 6 ml L^{-1} nano-DAP foliar spray provides a balanced approach towards sustainable agriculture, optimizing resources effectively.

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