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Research Article

Evaluating 4R Phosphorus Stewardship for Stress Resilient Sunflower Production

[a,b]Javaria Afzal Arain, [a]Zia-ul-hassan, [c]Nawal Memon, [a]Naheed Akhter Talpur, [d]Inzamam Ali Jamali, [e]Hajra Khan, [f]Ghulam Hussain Jatoi, [b]Nizamuddin Depar

[a] *Department of Soil Science, Sindh Agriculture University, Tandojam, Pakistan.*
[b] *Soil & Environmental Sciences Division, Nuclear Institute of Agriculture, Tandojam, Pakistan.*
[c] *Department of Agriculture Extension, Government of Sindh, Hyderabad, Pakistan.*
[d] *Sindh Agriculture & Water Transformation Project (SWAT), Tandojam, Pakistan.*
[e] *Oilseeds Research Institute, Agriculture Research Centre, Tandojam, Pakistan.*
[f] *Department of Plant Pathology, Sindh Agriculture University, Tandojam, Pakistan.*

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ABSTRACT

The 4R nutrient stewardship framework (right source, right rate, right time, and right place) is a well-established strategy for promoting low-input, stress-resilient, and sustainable crop production. A field experiment was conducted to evaluate sunflower response to 4R-based phosphorus (P) management, using a randomized complete block split-split plot design. The treatments included two P application methods (banding near seed rows and broadcasting), two P sources [monoammonium phosphate (MAP) and diammonium phosphate (DAP)], and five P rates (0, 30, 60, 90, and 120 kg P_2O_5 ha^{-1}), applied at sowing. Banding was found to be the superior application method, while MAP significantly enhanced plant height, head diameter, 1000-achene weight, and P concentrations in leaves and grains compared to DAP. The highest values for growth, yield, and oil content were recorded at 120 kg P_2O_5 ha^{-1}. The interaction between P source and method was non-significant; however, significant interactions were observed between application method and P rate for achene yield, stalk and leaf P concentrations, and oil content. Moreover, the interaction between P source and rate significantly influenced these parameters. A three-way interaction (source × method × rate) was significant for stalk P concentration and oil content. Overall, the best performance was achieved with 120 kg P_2O_5 ha^{-1} of MAP applied via banding near seed rows at sowing. Nevertheless, banded applications of 30 and 90 kg P_2O_5 ha^{-1} were found suitable for low- and high-input economic sunflower production, respectively. These findings align with 4R principles and promote P-efficient, resilient, and profitable sunflower cultivation.

Corresponding Author: Zia-ul-hassan
Email: zhnshah@gmail.com

Introduction

Sunflower (*Helianthus annuus* L.) is an important oilseed crop cultivated worldwide. Globally, sunflower contributes approximately 9% to the total edible oil production among oil-yielding crops and fruits (FAO, 2024). Sunflower oil is a blend of saturated and polyunsaturated fats, which help regulate high serum cholesterol levels. It is also a rich source of essential nutrients and vitamins such as vitamin E, B6, and folic acid (Adeleke and Babalola, 2020).

In Pakistan, sunflower is considered a vital oilseed crop and a significant contributor to edible oil production. However, recent statistics indicate a substantial decline in both the area under cultivation and production, by approximately 144% and 96%, respectively, compared to data from the previous decade (GoP, 2025). This decline highlights an urgent need to boost sunflower production to meet the growing edible oil demand of the country.

Phosphorus (P) plays a pivotal role in plant growth, biomass accumulation, achene yield, and oil quality traits in sunflower (Khan, 2011; Singh et al., 2017). As a key macronutrient, phosphorus is essential for energy transfer, enzymatic activity, metabolic processes, root development, yield enhancement (Abbadi and Gerendás, 2011; Pang et al., 2024), and improvement of both oil quantity and quality (Abbadi and Gerendás, 2015). Despite its importance, approximately 90% of soils in Pakistan are deficient in available phosphorus (<10 mg kg^{-1}) (Memon, 1996), and the use efficiency of soil-applied P fertilizers is estimated to be only 20-25% (Vishandas et al., 2006).

Recent studies confirm that phosphorus deficiency significantly restricts plant growth and adversely affects physiological development (Memon et al., 2024; Zia-ul-hassan et al., 2024). Therefore, the development and implementation of the 4R nutrient stewardship framework, applying the right source, at the right rate, at the right time, and in the right place, is crucial for improving P-use efficiency and achieving sustainable achene and oil production in sunflower. This approach could also help reduce Pakistan's reliance on edible oil imports.

Among the several factors limiting sunflower productivity, poor nutrient management, especially imbalanced phosphorus fertilization, is a critical constraint. Farmers in Pakistan commonly apply nitrogenous fertilizers in excess while neglecting adequate phosphate application. This imbalance not only exacerbates phosphorus deficiency but also reduces nitrogen use efficiency (GoP, 2025). Furthermore, the chemical nature of Pakistani soils, which are typically alkaline and calcareous, leads to phosphorus fixation through precipitation with calcium, forming relatively insoluble calcium phosphate compounds.

Addressing soil constraints and applying fertilizers appropriately are essential for maximizing crop productivity. Incorrect nutrient application methods can significantly affect crop growth and yield (Uddin et al., 2020). In contrast, balanced nutrient management has been shown to enhance crop productivity, while inappropriate fertilizer sources, doses, or methods can lead to nutrient loss and reduced yields (Majumdar et al., 2016). Effective fertilizer management practices offer considerable economic, environmental, and social benefits (IFA, 2009).

The 4R nutrient stewardship concept provides a promising strategy to improve P-use efficiency, reduce fertilizer losses, and mitigate environmental pollution. It emphasizes applying the correct nutrient source, at the correct rate, in the correct place, and at the correct time to support a sustainable and productive agricultural system (Jat et al., 2015; Reetz et al., 2015).

This field study was undertaken to develop and evaluate a practical and effective 4R phosphorus management framework aimed at optimizing phosphorus use efficiency in sunflower cultivation. Although previous research has often focused on individual aspects of phosphorus management, such as method, dose, timing, or source, this study seeks to integrate all four components to assess their combined effect on yield and oil production. The main goal is to enhance agricultural productivity while minimizing environmental risks, thereby promoting sustainable sunflower cultivation in Pakistan.

Materials and Methods

Experimental details

A field experiment was conducted at the Nuclear Institute of Agriculture (NIA), Tandojam, Sindh, Pakistan. The experiment was laid out in a Randomized Complete Block Design (RCBD) with a split-split plot arrangement and three replications. The physicochemical properties of the experimental field were analyzed before sowing, following the procedures outlined by Ryan et al. (2001). The soil analysis revealed a clay loam texture, alkaline pH (7.5), non-saline conditions (EC 1.3 dS m^{-1}), medium organic matter content (0.98%), and marginal levels of available phosphorus (4.6 mg kg^{-1} soil).

The sunflower hybrid 'Hysun-39' was used as the test crop. Seeds were surface-sterilized with 1.2% sodium hypochlorite for 10 min and rinsed thoroughly with deionized water. Sowing was done in wide plots (5 × 2 m), each consisting of four rows spaced 75 cm apart. Thinning was performed two weeks after sowing to maintain optimal plant population. A total of five irrigations were applied during the crop growth period.

4R phosphorus administration

Phosphorus application timings and placement methods, broadcasting at land preparation and banding near seed rows at sowing, were assigned to the main plots. Each main plot was split into two sub-plots receiving either monoammonium phosphate (MAP) or diammonium phosphate (DAP) as the phosphorus source. Each sub-plot was further divided into five sub-sub-plots receiving phosphorus fertilizer at rates of 0, 30, 60, 90, and 120 kg P_2O_5 ha^{-1}.

Fertilization of sunflower

A blanket dose of 150 kg nitrogen (N), 50 kg potassium (K), and 5 kg zinc (Zn) ha^{-1} was applied to the sunflower crop. Half of the nitrogen was applied at sowing, while the remaining half and the full dose of zinc were applied with the first irrigation. Urea, potassium sulfate, and zinc sulfate were used as sources of N, K, and Zn, respectively. Phosphorus was supplied according to treatment plans using MAP and DAP.

Recording of observations

The crop was harvested at physiological maturity, 120 days after sowing. Ten plants were randomly selected from each experimental unit to record data on plant height (cm), head diameter (cm), number of achenes per head, 1000-achene weight (g), achene yield, and stalk yield (kg ha^{-1}).

Plant phosphorus analysis and efficiency calculations

Plant samples (shoots and achenes) were oven-dried at 70-80°C for 72 h until a constant weight was achieved. The dried samples were ground using a stainless-steel grinder and passed through a 100-mesh sieve. Phosphorus concentration was determined spectrophotometrically at 470 nm (U-2900, Hitachi), using the double acid digestion method (HNO_3:$HClO_4$, 2:1) as described by Rashid (1986). Achene phosphorus uptake was calculated as described by Zia-ul-hassan et al. (2011):

Achene P uptake = Achene P concentration × Achene yield

Achene phosphorus use efficiency was calculated using the following formula (Baligar et al., 2001):

Achene P use efficiency = [Achene yield (30, 60, 90,120 kg P_2O_5 ha^{-1}) - Achene yield (control)] ÷ respective amount of P fertilizer applied

Oil and protein analysis

Protein content was determined using the Kjeldahl method (FOSS-2200), with modifications based on Sunil et al. (2015). One gram of sample was digested with 15 ml sulfuric acid and a catalyst at 420°C. After digestion and distillation, the sample was titrated with 0.2 N HCl. A nitrogen-to-protein conversion factor of 5.88 was used.

Oil content (%) was determined using the traditional Soxhlet extraction method. Ground samples were extracted using petroleum ether at 60°C for 6 h. The solvent was then evaporated using a rotary evaporator, and the extracted oil was stored in amber vials at 18°C until analysis.

Statistical analysis

All data were collected in triplicate and subjected to analysis of variance (ANOVA) using Statistix® software, version 10.0. Mean separation was performed using Tukey's Honest Significant Difference (HSD) test at a 0.05 probability level. Graphs were prepared using Microsoft Excel (365 version).

Results

Growth parameters

The experimental results demonstrated that application of P significantly enhanced all measured growth parameters, regardless of the method or source used (Table 1). Increasing the P rate led to higher dry weights. The application of 120 kg P_2O_5 ha^{-1} resulted in the highest head diameter and number of achenes per head, whereas plant height showed a comparable response at 90 kg P_2O_5 ha^{-1} (Table 1).

The methods and sources of P application influenced the growth parameters differently. The number of achenes per head was significantly increased under both application methods. However, overall growth parameters were more favorably influenced by the banding method compared to broadcasting (Table 1). A significant difference between the two P sources was observed for plant height and head diameter, while the number of achenes per head remained statistically non-significant between the two sources.

The interaction between P source and method was found to be non-significant for all three growth traits of the sunflower hybrid. Similarly, the interactions between P method × P dose and P source × P dose were also non-significant for plant height and head diameter. However, a highly significant effect was observed for the number of achenes per head, with the maximum number (1509.2) recorded under the combination of banding method and 120 kg P_2O_5 ha^{-1} (Table 2).

Table 1. Effect of different P methods (PM), P sources (PS), and P doses (PD) on various yield traits and yield of sunflower.

P Treatments	Plant height (cm)	Disc dia (cm)	Achene per disc	1000 achene weight (g)	Achene yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
P Methods (PM)						
Banding (BND)	139.9	26.38	1159 a	49.93 a	3884 a	5644 a
Broadcasting (BRD)	137.7	23.94	1089 b	44.50 b	3460 b	5207 b
Mean Squares	76.84	89.548	73689	442.817	2688336	2863224
F-ratio	3.35	14.51	122.83	19.93	18.9	216.93
P-ratio	0.2088	0.0625	0.008	0.0467	0.049	0.0046
HSD0.05	NS	NS	27.211	5.2364	418.89	127.63
P Sources (PS)						
MAP	140.81 a	26.01 a	1129.9	48.10 a	3744.3	5424.1
DAP	136.81 b	24.31 b	1118.4	46.33 b	3600.8	5427.8
Mean Squares	240.4000	43.18	2385	46.817	308912	205
F-ratio	14.0100	21.33	2.33	14.26	3.79	0.126
P-ratio	0.0201	0.0099	0.202	0.0195	0.1235	0.9587
HSD0.05	3.0	1.0199	NS	1.299	NS	NS
P Doses (PD)						
P0	118.17 d	14.61 e	844.1 e	35.50 e	2525.0 d	4692.7 e
P30	130.33 c	21.78 d	943.0 d	45.67 d	3371.3 c	5015.2 d
P60	138.92 b	25.07 c	1079.7 c	48.58 c	3954.2 b	5566.1 c
P90	153.39 a	30.92 b	1288.8 b	50.75 b	4139.1 ab	5745.7 b
P120	153.25 a	33.42 a	1465.2 a	55.58 a	4373.1 a	6110 a
Mean Squares	2757.5	672.881	769990	672.108	6586002	3888684
F-ratio	145.8	199.62	965.88	370.82	80.44	120
P-ratio	0.000	0.000	0.000	0.000	0.000	0
HSD0.05	3.6	1.5268	23.479	1.1195	237.95	149.7

The three-way interaction among P method × P source × P dose was not significant for any of the growth parameters. Nevertheless, the maximum plant height was observed under the treatments BND × DAP × P120 and BRD × MAP × P90, whereas the maximum head diameter and achene yield were recorded under BND × MAP × P120 (Table 3).

Yield parameters

A linear response was observed for the application of P method and P sources on sunflower yield, with a significant difference between banding and broadcasting methods for 1000-grain weight, achene yield, and stalk yield. The highest mean values were recorded under the banding method compared to broadcasting.

P sources had no significant effect on achene and stalk yield, but a significant difference was noted for 1000-grain weight. Among the P sources, MAP consistently produced higher values for all yield parameters compared to DAP. Overall, the yield parameters reached their maximum at the application rate of 120 kg P_2O_5 ha^{-1} (Table 1).

The interaction between P source × P method was found to be non-significant for all yield traits. However, significant interactions were observed between P method × P dose and P source × P dose, showing positive effects on 1000-grain weight, achene yield, and stalk yield. The highest values for all yield parameters in the P method × P dose interaction were recorded under banding at 120 kg P_2O_5 ha^{-1}. Similarly, in the P source × P dose interaction, the maximum achene weight, achene yield, and stalk yield were obtained with MAP at 120 kg P_2O_5 ha^{-1} (Table 2).

Although the three-way interaction (P method × P source × P dose) was not statistically significant, the highest increases in achene weight, stalk, and achene yield were observed with the application of MAP at 120 kg P_2O_5 ha^{-1} using the banding method (Table 3).

Table 2. Effect of interaction of different P methods (PM), P sources (PS), and P doses (PD) on various yield traits and yield of sunflower.

Interaction	Plant height (cm)	Disc dia (cm)	Achene per disc	1000 achene weight (g)	Achene yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
PM×PS Interaction						
BND×MAP	142.49	26.93	1171.2	51.07	3988.2	5727.5
BND×DAP	137.4	25.83	1147.2	48.8	3780.2	5561.2
BRD×MAP	139.14	25.09	1088.5	45.13	3500.4	2594.3
BRD×DAP	136.22	22.79	1089.7	43.87	3421.3	5120.6
Mean Squares	17.6	5.34	2385	3.75	62288	433670
F-ratio	1.03	2.64	2.33	1.14	0.76	6.41
P-ratio	0.3683	0.1796	0.202	0.3454	0.4316	0.0645
HSD0.05	NS	NS	NS	NS	NS	NS
PM×PD Interaction						
BND×P0	119.38	14.78	844.3 gh	35.83 g	2486.7 f	4684.8 e
BND×P30	129.17	22.67	984.0 f	49.0 d	3411.3 de	5196.2 d
BND×P60	142.17	26.4	1107.8 e	51.67 c	4196.3 b	5821.5 c
BND×P90	152.83	33.03	1350.8 c	54.0 b	4545.3 a	6127.7 b
BND×P120	156.17	35.03	1509.2 a	59.17 a	4781.5 a	6391.7 a
BRD×P0	116.95	14.43	843.9 h	35.17 g	2563.3 f	4700.5 e
BRD×P30	131.5	20.9	902.0 g	42.33 f	3331.3 e	4834.2 e
BRD×P60	135.67	23.73	1051.6 ef	45.5 e	3712.0 cd	5310.7 d
BRD×P90	153.95	28.82	1226.8 d	47.5 de	3733.0 bcd	5363.7 d
BRD×P120	150.33	31.82	1421.2 b	52.0 bc	2964.7 bc	5828.3 c
Mean Squares	47.46	6.474	6317	21.692	508263	254154
F-ratio	2.51	1.92	7.92	11.97	6.21	7.84
P-ratio	0.0613	0.131	0.0001	0.000	0.0008	0.0002
HSD0.05	NS	NS	38.074	5.2492	336.51	219.19
PS×PD Interaction						
MAP×P0	119.5	14.57	842.6	33.83	2531	4677.2 d
MAP×P30	133.45	22.67	949.1	46.67	3525.3	4832.5 d
MAP×P60	140.5	26.22	1091.1	49.5	3971.3	5576.5 b
MAP×P90	157	32.32	1293	52	4222.3	5919.3 a
MAP×P120	153.62	34.28	1473.7	56.5	4471.5	6114.8 a
DAP×P0	116.83	14.65	845.6	35.17	2591	4708.2 d
DAP×P30	127.22	20.9	936.9	44.67	3217.3	5197.8 c
DAP×P60	137.33	23.92	1068.3	47.67	3937	5555.7 b
DAP×P90	149.78	29.53	1284.7	49.5	4055.9	5572.0 b
DAP×P120	152.88	3.539	1456.7	54.67	4274.7	6105.2 a
Mean Squares	21.36	3.539	285	1.358	44726	191647
F-ratio	1.13	1.05	0.36	0.75	0.55	5.91
P-ratio	0.3601	0.3971	0.8372	0.5657	0.703	0.0011
HSD0.05	NS	NS	NS	NS	NS	262.68

Table 3. Effect of interaction of different P methods (PM), P sources (PS), and P doses (PD) on various yield traits and yield of sunflower.

Interaction	Plant height (cm)	Disc dia (cm)	Achene per disc	1000 achene weight (g)	Achene yield (kg ha^{-1})	Stalk yield (kg ha^{-1})
BND×MAP×P0	122.77	14.67	843	36	2565.3	4812.7
BND×MAP×P30	133.67	23.33	1000.8	50	3434	5100.3
BND×MAP×P60	146	27.57	1124.7	53.33	4246	5894.3
BND×MAP×P90	155.67	33.43	1376.4	56	4722.7	6366
BND×MAP×P120	154.33	35.67	1511.4	60	4972.9	6464.3
BND×DAP×P0	116	14.9	845.6	35.67	2496.7	4557
BND×DAP×P30	124.67	22	967.2	48	3616.7	5392
BND×DAP×P60	138.33	25.23	1090.8	50	3696.7	5748.7
BND×DAP×P90	150	32.63	1325.3	52	3722	5889.3
BND×DAP×P120	158	34.4	1507	58.33	3970	6319
BRD×MAP×P0	116.23	14.47	842.2	35.67	2408	4541.7
BRD×MAP×P30	133.23	22	897.4	43.33	3388.7	4564.7
BRD×MAP×P60	135	24.87	1057.5	45.67	4146.7	5258.7
BRD×MAP×P90	158.33	31.2	1209.5	48	4367.9	5472.7
BRD×MAP×P120	152.9	32.9	1436.1	53	4590	5765.3
BRD×DAP×P0	117.67	14.4	845.6	34.67	2630	4859.3
BRD×DAP×P30	129.77	19.8	906.5	41.33	3046	5103.7
BRD×DAP×P60	136.33	22.6	1045.8	45.33	37727.3	5362.7
BRD×DAP×P90	149.57	26.43	1244.2	47	3744	5254.7
BRD×DAP×P120	147.77	30.73	1406.4	51	3959.3	5891.3
Mean Squares	45.46	1.926	1337	2.542	107789	13873
F-ratio	2.4	0.57	1.68	1.4	1.32	0.43
P-ratio	0.0702	0.6854	0.1796	0.2555	0.2849	0.7872
HSD0.05	NS	NS	NS	NS	NS	NS

Phosphorus concentration in plant

The results indicated that P application methods had significant effects on P concentrations in various plant parts, including the stalk, leaf, and seed. The highest mean P concentration across all plant parts was recorded with the banding method.

Similarly, P sources positively influenced P concentrations in stalks and leaves, with MAP proving more effective than DAP. Furthermore, the different levels of P fertilizer significantly ($p < 0.05$) affected the P concentration in sunflower achenes, stalks, and leaves. The highest P concentration in leaves, stalks, and achenes was observed at the application rate of 120 kg P_2O_5 ha^{-1} (Table 4).

The data also revealed interactions among P sources, P application methods, and P doses in sunflower. The interaction between P sources and application methods on P concentration in leaves, stalks, and achenes was not statistically significant ($p > 0.05$). However, a significant interaction ($p < 0.05$) between PM and PD was observed for P concentrations in stalks and leaves, while the interaction was non-significant for achenes. The highest mean values for stalk (0.1535) and leaf (0.2148) P concentrations were obtained from the banding method combined with the 120 kg P_2O_5 ha^{-1} dose (Table 5).

A significant interaction ($p < 0.05$) between PS and PD was also found for P concentrations in stalks and leaves, whereas it remained non-significant for achenes. The highest P concentrations for stalk (0.1430) and leaf (0.2110) were recorded when MAP was applied at 120 kg P_2O_5 ha^{-1} (Table 5).

Statistically, the three-way interaction among PM × PS × PD was non-significant ($p > 0.05$) for P concentrations in leaves and achenes. However, a significant effect was observed for stalk P concentration, with the maximum values recorded for BND × MAP × PD combinations (0.1547 and 0.1523, respectively) (Table 6).

Table 4. P concentration and quality traits of sunflower achene grown with two P sources, application methods and treatments

P Treatments	Achene P concentration (%)	Stalk P concentration (%)	Leaf P concentration (%)	Achene oil content (%)	Achene protein (%)
P Methods (PM)					
Banding (BRD)	0.3490 A	0.0975 A	0.1492 A	42.697 A	19.393
Broadcasting (BND)	0.3344 B	0.0862 B	0.1280 B	40.950 B	18.607
Mean Squares	0.0032	1.915	0.0067	45.763	9.2827
F-ratio	25.9	736.67	60.84	91.49	5.14
P-ratio	0.0365	0.0014	0.016	0.0108	0.1515
HSD0.05	0.0123	1.791	0.0117	0.7857	NS
P Sources (PS)					
MAP	0.3493	0.0962 A	0.1470 A	42.18	19.083
DAP	0.3341	0.0875 B	0.1302 B	41.467	18.917
Mean Squares	0.00347	1.153	0.00423	7.633	0.4167
F-ratio	3.72	224.57	47.68	4.99	0.19
P-ratio	0.1261	0.0001	0.0023	0.0893	0.688
HSD0.05	NS	1.624	6.755	NS	NS
P Doses (PD)					
P0	0.1504 E	0.0274 E	0.0720 E	34.017 E	15.192 D
P30	0.2666 D	0.0736 D	0.1118 D	40.883 D	17.042 C
P60	0.3487 C	0.0975 C	0.1393 C	42.533 C	19.800 B
P90	0.4433 B	0.1223 B	0.1694 B	44.800 B	21.358 A
P120	0.4992 A	0.1384 A	0.2005 A	46.882 A	21.608 A
Mean Squares	0.2323	0.02284	0.0298	290.338	94.0308
F-ratio	833.81	3210.04	611.9	481.77	45.37
P-ratio	0.00	0.0000	0.0000	0.0000	0.0000
HSD0.05	0.0139	2.218	5.803	0.317	1.1971

Achene P uptake

The analysis of variance for P uptake revealed that all sources of variation were non-significant, except for phosphorus application methods, doses, and their interaction (Figure 1). Among the methods, banding was found to be superior to broadcasting. P uptake by sunflower increased with increasing P doses, reaching a maximum at 120 kg P_2O_5 ha^{-1}, and was lowest in the control (no P application). The interaction between application method and dose indicated that the highest P uptake occurred when 120 kg P_2O_5 ha^{-1} was applied through banding (Figure 2). Notably, P uptake with banding at 90 kg P_2O_5 ha^{-1} was statistically comparable to broadcasting at 120 kg P_2O_5 ha^{-1}. Overall, banding was more effective than broadcasting at 60, 90, and 120 kg P_2O_5 ha^{-1}. However, at 30 kg P_2O_5 ha^{-1}, there was no significant difference between the two methods.

Achene P-use efficiency

The analysis of variance for achene P-use efficiency showed that all sources of variation were non-significant, except for P doses. P-use efficiency decreased with increasing P application rates, indicating that an application rate of 30 kg P_2O_5 ha^{-1} was sufficient to achieve statistically optimum achene yield in sunflower (Figure 3).

Achene oil and protein content

The oil content in sunflower achenes was significantly affected by P application, whereas protein content remained unaffected. Among the P application methods, band placement resulted in the highest oil and protein contents compared to broadcasting. Although the effect of P sources on oil and protein content was non-significant, all P application rates had a significant influence on both parameters. The HSD values for P treatment means were 0.317 for oil content and 1.1971 for protein content at $p < 0.05$. The highest oil content (46.8%) was recorded at a P application rate of 120 kg P_2O_5 ha^{-1}. Similarly, the maximum protein content (21.6%) was also observed at 120 kg P_2O_5 ha^{-1}, followed closely by 21.3% at 100 kg P_2O_5 ha^{-1} (Table 4).

Table 5. Effect of PM×PS, PM×PD and PS×PD interactions on P concentration and quality traits of sunflower achene.

Interaction	% Achene P concentration	% Stalk P concentration	% Leaf P concentration	% Achene oil content	% Achene protein
PM×PS Interaction					
BND×MAP	0.3581	0.1017	0.1587	42.407	19.44
BND×DAP	0.3398	0.0933	0.1396	42.987	19.347
BRD×MAP	0.3404	0.0907	0.1353	40.527	18.727
BRD×DAP	0.3283	0.0817	0.1208	41.373	18.487
Mean Squares	0.00015	1.35	0.00008	0.267	0.0807
F-ratio	0.16	0.26	0.92	0.17	0.04
P-ratio	0.7113	0.6351	0.3918	0.6978	0.8585
HSD0.05	NS	NS	NS	NS	NS
PM×PD Interaction					
BND×P0	0.1505	0.0273 I	0.0732 F	33.517 G	15.2
BND×P30	0.2735	0.0757 G	0.1187 D	41.667 E	18.15
BND×P60	0.3607	0.1040 E	0.1508 C	43.267 D	19.667
BND×P90	0.4523	0.1270 B	0.1883 B	46.433 B	21.95
BND×P120	0.5078	0.1535 A	0.2148 A	48.600 A	22
BRD×P0	0.1503	0.0275 I	0.0708 F	34.517 G	15.183
BRD×P30	0.2597	0.0715 H	0.1050 E	40.100 F	15.933
BRD×P60	0.3368	0.0910 F	0.1277 D	41.800 E	19.933
BRD×P90	0.4343	0.1177 D	0.1505 C	43.167 D	21.267
BRD×P120	0.4907	0.1233 C	0.1862 B	45.167 C	20.717
Mean Squares	0.00023	4.088	0.00056	9.608	3.0035
F-ratio	0.84	57.44	11.54	15.94	1.45
P-ratio	0.5097	0.0000	0.0000	0.0000	0.2407
HSD0.05	NS	3.204	0.0129	1.0688	NS
PS×PD Interaction					
MAP×P0	0.1502	0.0280 I	0.0727 G	33.333 G	15.217
MAP×P30	0.2755	0.0765 G	0.1192 E	40.3 E	17.967
MAP×P60	0.3623	0.0167 E	0.1598 D	41.967 CD	19.633
MAP×P90	0.4538	0.1270 C	0.1790 C	44.933 B	21.45
MAP×P120	0.5045	0.1430 A	0.2110 A	46.8 A	21.15
DAP×P0	0.1507	0.0268 I	0.0713 G	34.7 F	15.167
DAP×P30	0.2577	0.0707 H	0.1045 F	41.467 DE	16.117
DAP×P60	0.3352	0.0883 F	0.1253 E	41.967 DE	19.967
DAP×P90	0.4328	0.1177 D	0.1598 D	44.667 B	21.767
DAP×P120	0.494	0.1338 B	0.1900 B	46.967 A	21.567
Mean Squares	0.00034	1.188	0.00029	1.551	2.7533
F-ratio	1.22	16.69	5.99	2.57	1.33
P-ratio	0.3226	0	0.001	0.0565	0.2806
HSD0.05	NS	3.218	9.863	1.1913	NS

Table 6. Effect of PM×PS×PD interaction on P concentration and quality traits of sunflower achene.

P Treatments	Achene P concentration (%)	Stalk P concentration (%)	Leaf P concentration (%)	Achene oil content (%)	Achene protein (%)
BND×MAP×P0	0.1503	0.0277 K	0.0747	32.633 I	15.2
BND×MAP×P30	0.2863	0.0793 I	0.126	41.667 EF	18.167
BND×MAP×P60	0.3757	0.1170 D	0.1643	43.067 D	19.667
BND×MAP×P90	0.464	0.1300 B	0.2003	46.333 BC	22.033
BND×MAP×P120	0.5143	0.1547 A	0.2283	48.333 A	22.133
BND×DAP×P0	0.1507	0.0270 K	0.0717	34.400 H	15.2
BND×DAP×P30	0.2607	0.0720 J	0.1113	41.667 EF	18.133
BND×DAP×P60	0.3457	0.0910 G	0.1373	43.467 D	19.667
BND×DAP×P90	0.4407	0.1240 C	0.1763	46.533 B	21.867
BND×DAP×P120	0.5013	0.1523 A	0.2013	48.867 A	21.867
BRD×MAP×P0	0.15	0.0283 K	0.0707	34.033 H	15.233
BRD×MAP×P30	0.2647	0.0737 J	0.1123	38.933 G	17.767
BRD×MAP×P60	0.349	0.0963 F	0.142	40.867 F	19.6
BRD×MAP×P90	0.4437	0.1240 C	0.1577	43.533 D	20.867
BRD×MAP×P120	0.4947	0.1313 B	0.1937	45.267 BC	20.167
BRD×DAP×P0	0.1507	0.0267 K	0.071	35.000 H	15.133
BRD×DAP×P30	0.2547	0.0693 J	0.0977	41.267 F	14.1
BRD×DAP×P60	0.3247	0.0857 H	0.1133	42.800 DE	20.267
BRD×DAP×P90	0.425	0.1113 E	0.1433	42.733 DE	21.667
BRD×DAP×P120	0.4867	0.1153 DE	0.1787	43.533 D	21.267
Mean Squares	0.00002	8.897	0.00003	1.742	3.0657
F-ratio	0.09	12.5	0.55	2.89	1.48
P-ratio	0.9861	0.000	0.7014	0.0378	0.2316
HSD0.05	NS	4.54E-03	NS	1.378	NS

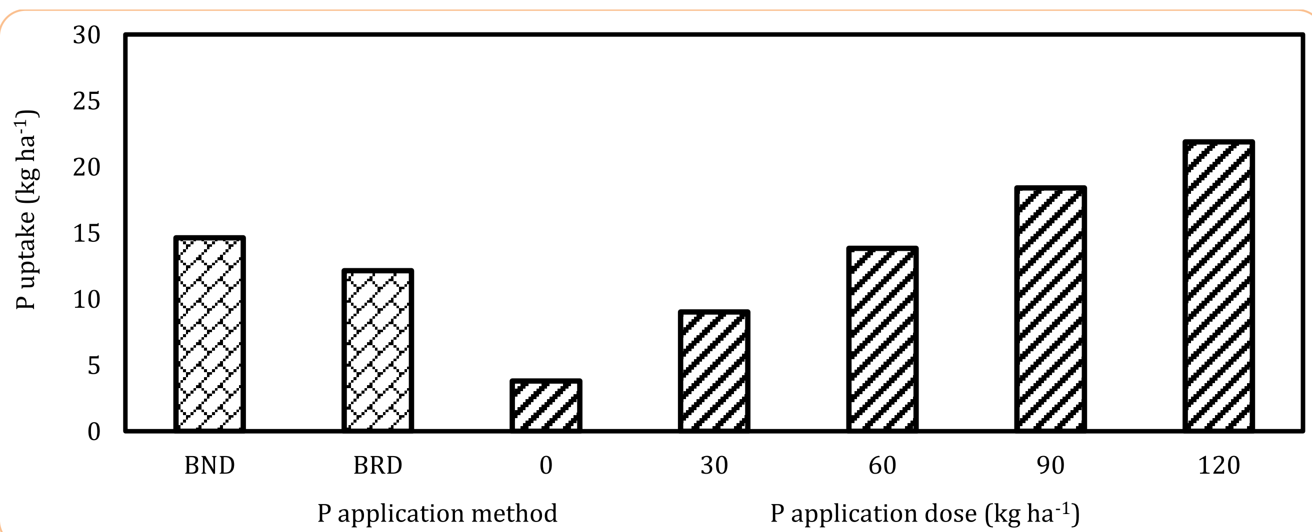

Figure 1. Phosphorus uptake of sunflower achene as affected by phosphorus application methods and doses (BND = Banding, BRD = Broadcasting, 0 to 120 = P application doses in kg ha^{-1}).

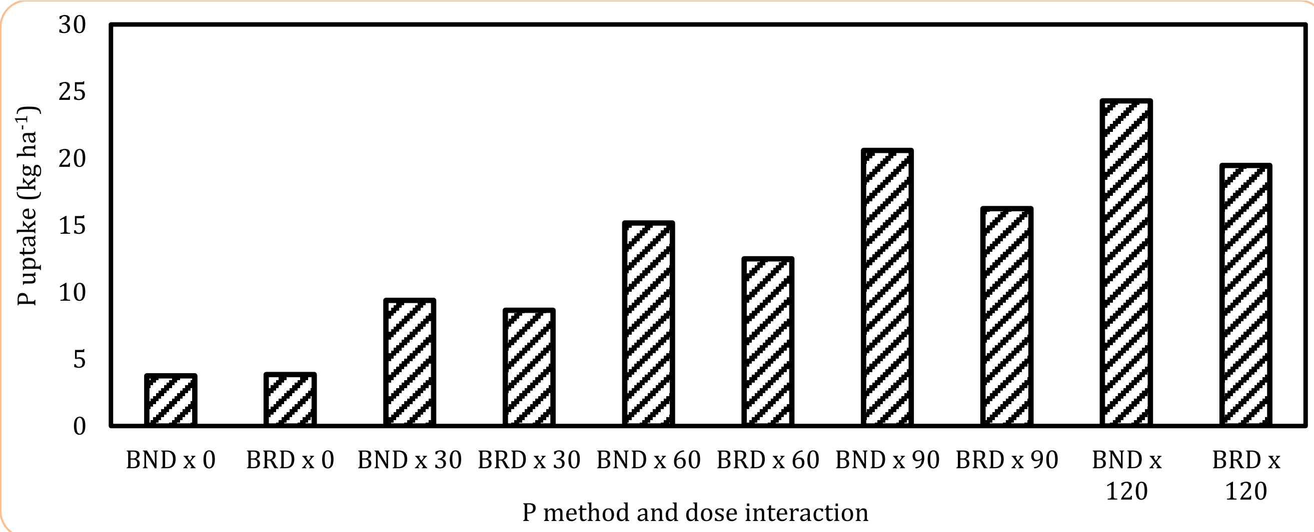

Figure 2. Phosphorus uptake of sunflower achene as affected by interaction between phosphorus application methods and doses (BND = Banding, BRD Broadcasting, 0 to 120 = P application doses in kg ha^{-1}).

The interactive effects of P sources and P application methods on oil and protein content were non-significant ($p > 0.05$). However, the highest mean oil content (42.9%) was observed under the BND × AP combination; while the maximum protein content (19.4%) was recorded in the BND × DAP treatment.

A significant interaction (LSD = 1.068) was found between P application methods and P doses. The highest oil content (48.600%) was obtained in the BND × P120 treatment, followed by 46.433% in BND × P90. In contrast, the interaction between P application method and P dose was non-significant for protein content (Table 5).

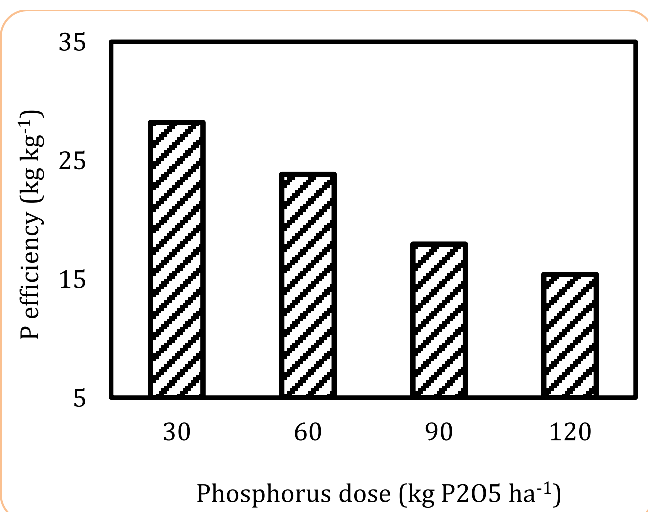

Figure 3. Phosphorus efficiency of sunflower achene (kg achene yield per kg applied P) as affected by P application doses.

The interaction between P sources and P doses significantly influenced achene oil content, with an HSD value of 1.1913 at $p < 0.05$. The maximum oil contents were recorded as 46.9% in DAP × P120 and 46.8% in MAP × P120 treatments, respectively. However, this interaction had no significant effect on achene protein content. The highest protein content (21.7%) was observed in the DAP × P90 treatment (Table 5).

A three-way interaction among P source, P application method, and P dose significantly affected oil content (Table 6), with an HSD value of 1.378 at $p < 0.05$. The highest oil contents were recorded in the BND × MAP × P120 (48.333%) and BND × DAP × P120 (48.867%) treatments. However, this three-way interaction was not significant in terms of protein content (Table 6).

Discussion

The application of P significantly improves stem diameter, leaf and capitulum dry matter, as well as yield and oil content in sunflower (Abbadi and Gerendás, 2015). According to Fernandez and Rubio (2015), P fertilization not only enhances growth and yield parameters but also promotes root architecture by increasing root length, biomass, and root density in sunflower. Therefore, proper P management, considering the timing, rate, method, and placement, can optimize sunflower growth and productivity. The findings of the present study highlight the multifaceted effects of 4R nutrient stewardship (right source, right rate, right time, right place) in ensuring sustainable and productive sunflower cultivation.

In this study, all measured growth parameters, including plant height, head diameter, and achenes per head, were generally improved with P application compared to the control and varied significantly among application methods. Sunflower growth parameters showed greater improvement under band placement than broadcast application. This is attributed to enhanced P availability near the root zone, improved P utilization, and reduced P precipitation and fixation with soil particles in band placement (Mortvedt et al., 1996; Rehim et al., 2012).

Selecting an appropriate P source is crucial. Li et al. (2014) reported that both MAP and DAP are effective due to their high solubility and rapid nutrient availability. However, in the present study, MAP application resulted in the maximum improvement in all growth and yield traits compared to DAP. Johnston and Bruulsema (2014) also indicated that MAP is a highly efficient source of both P and N, particularly beneficial during early growth stages when P availability is restricted due to fixation. MAP creates an acidic microenvironment around the rhizosphere, enhancing P availability in high-pH calcareous soils.

Soares et al. (2020) suggested that a P application rate of 100 to 150 kg P_2O_5 ha^{-1} provides optimal conditions for sunflower growth. Based on the current findings, P requirements for sunflower range between 100-150 kg P_2O_5 ha^{-1}, but these values can vary depending on soil type, location, and variety. In a recent study conducted on alkaline soils, varying P levels were applied, and it was observed that all growth and yield parameters of sunflower increased linearly with rising P application rates. However, no significant differences were noted between 80 and 100 kg P_2O_5 ha^{-1}, suggesting that while higher P rates may maximize yield, they may not be statistically superior to the optimal dose (Manzoor et al., 2024).

P plays a critical role in improving sunflower yield. Singh et al. (2017) reported that adequate P supply significantly enhances dry matter accumulation, growth rate, and ultimately boosts seed yield. Consistent with the present findings, the application of MAP through banding significantly increased 1000-achene weight, achene yield, and stalk biomass. Similar results have been reported in wheat, where band placement of P improved 1000-grain weight, grain yield, straw biomass, and total biological yield compared to broadcast and top-dressing methods. Deep band application of P has also been shown to improve yields in wheat and maize (Freiling et al., 2022).

Experimental results indicated that the highest P concentration in all plant parts was observed with banded P application at sowing. Band placement of P has been widely reported to increase P concentration and uptake compared to broadcasting (Freiling et al., 2022). Under P-deficient soils, the recommended rates can be safely applied through this method. Furthermore, seed band-placement is particularly effective as it delivers phosphorus directly to the root zone, thereby enhancing germination and early seedling vigor.

The band application of MAP and DAP fertilizers significantly improves P availability for plant uptake and increases P concentration in plant tissues (Grant and Flaten, 2019). In the current study, the highest P concentrations in achene, stalk, and leaves were recorded with MAP application via banding compared to DAP.

P uptake in sunflower increased significantly with band application as compared to broadcasting and increased linearly with increasing P fertilizer doses from 30 to 120 kg P_2O_5 ha^{-1}. Oliveira et al. (2022) also reported that P uptake increases with higher P rates, although P use efficiency may decline at excessive application levels.P fertilization also had a significant impact on oil and protein content. The highest percentages of both traits were observed at the maximum P application level with MAP. Soares et al. (2020) highlighted the critical role of phosphorus in enhancing oil production in sunflower. Khan (2011) demonstrated that application of 90 kg P_2O_5 ha^{-1} significantly increased oil content, oil yield, and protein levels in sunflower. Moreover, inappropriate or untimely P fertilization may hinder plant growth at early stages. In contrast, timely application improves achene yield and oil content (Ullah and Akmal, 2018).

Based on the results of this study and the reviewed literature, it can be concluded that maximum sunflower yield and oil content can be achieved by applying P as MAP through band placement at sowing, ideally at a rate of 90 kg P_2O_5 ha^{-1}. For resource-limited farmers, an economically viable option would be applying 30 kg P_2O_5 ha^{-1} through the same method.

Conclusion

The application of phosphorus fertilizers significantly improved sunflower growth, yield, oil content, and protein levels. The adoption of 4R nutrient stewardship enhanced achene yield, phosphorus use efficiency, and farm profitability while minimizing P losses and promoting environmental sustainability. Based on these findings, it is recommended that phosphorus should be applied through band placement near the seed row at sowing using monoammonium phosphate at either 30 kg P_2O_5 ha^{-1} (for economic production) or 90 kg P_2O_5 ha^{-1} (for maximum yield). Future studies are warranted to validate these findings under diverse agro-ecological conditions and further address the research gaps identified in this study.

Authors' Contributions

JAA and ZHN conceived the idea, wrote research proposal, won research grant from HEC, conducted and executed field study, performed statistical analysis, and wrote and edited all the drafts of manuscript; NM collected and recorded field data and performed plant analyses; NAT and IAJ processed all data, and prepared tables and figures; HK and ND performed achene oil and protein analyses; GHJ helped in finalizing the revised draft of manuscript and authors' responses to reviewers' comments; All authors thoroughly reviewed and endorsed final draft of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

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