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Band-application of phosphorus with farm manure improves phosphorus use efficiency, productivity, and net returns of wheat on sandy clay loam soil

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Abstract: Phosphorus use efficiency (PUE) is very low in alkaline calcareous soils; however, it can be improved by using suitable application methods along with farm manure (FM). The present field study was conducted to optimize phosphorus (P) levels and application methods in order to maximize wheat yield, PUE, and net returns on calcareous soils with and without FM application. Five P soil solution levels, i.e. 0.00, 0.05, 0.10, 0.20, and 0.30 mg P L^{-1}, were maintained according to the Freundlich model through the application of 0, 36, 61, 104, and 142 kg P_2O_5 ha^{-1}, respectively. The calculated P (0, 36, 61, 104, and 142 kg P_2O_5 ha^{-1}) was applied by broadcasting, band-placement, and top-dressing, with or without 300 kg ha^{-1} well-rotted FM. The results revealed that the band-placement technique at 104 kg P_2O_5 ha^{-1} improved PUE and wheat output with and without FM application. Furthermore, wheat grain and straw P uptake was high at 142 kg P_2O_5 ha^{-1}. In addition, protein content and Olsen P were high at 142 kg P_2O_5 ha^{-1}. The band-placement technique at 104 kg P_2O_5 ha^{-1} increased net returns and the cost/benefit ratio. FM application further augmented the productivity, PUE, and net returns under various P levels and application techniques. In conclusion, band-placement of P at 104 kg P_2O_5 ha^{-1} with FM improved yield, PUE, and net returns of wheat sown on sandy clay loam calcareous soils.

Key words: Freundlich model, phosphorus application methods, phosphorus uptake, phosphorus use efficiency, wheat yield

1. Introduction

Crop productivity is controlled by many factors, and mineral nutrition, especially phosphorus (P) fertilization, plays a central role (Channabasanagowda et al., 2008). It is an important component of nucleic acid, proteins, and ATP, which are energy-rich compounds that fuel the other metabolic processes. Moreover, it is an important constituent of carbohydrates, nitrogenous compounds, and certain coenzymes (Hussein, 2009). Hence, plants need sufficient P in their initial stages of growth to ensure high productivity (Grant et al., 2005). Nonetheless, P deficiency is the leading cause of lower crop productivity in Pakistan, as about 90% of soils in the country are P-deficient (Ahmad et al., 1992; Alam et al., 1994).

Fertilizer use efficiency (FUE) is a tool to measure the potential of crops for total dry matter production and economic yield. In Pakistan, most of the soils are alkaline and calcareous in nature. As a result, P use efficiency (PUE) is well below that of other nutrients (Saleem, 1992); PUE is less than 25% in Pakistan (Ahmad and Rashid, 2003). Furthermore, the availability of adsorbed P decreased gradually in soil solution and subsequently reduced the PUE in calcareous soils (Delgado et al., 2002). The availability of P in soil solution depends on soil pH, the rate of solid-phase diffusion of P, reaction time, amount of organic matter, soil temperature, and clay type of the soil. Therefore, P fixation is important in the interpretation of soil tests and nutrient recommendations. Hence, adjustment of the P dose specific to the site and crop is very important for good crop production (Nisar et al., 1992; Rehim et al., 2012a, 2012b).

Over 80% of applied P becomes fixed and thus only a small portion of added P goes into soil solution, where it is either precipitated or taken up by the plants (Leytem and Mikkelsen, 2005). Plant roots absorb P only from soil solution (Johnston et al., 1999); thus, external soil solution

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P needs may be a plant characteristic (Fox, 1981). When P is applied in soil, a major part is adsorbed in the exchange complex, and a lesser amount is released into the soil solution for the plant roots to absorb. Once the level of soil solution P required for optimum growth of the crop is determined, we can utilize adsorption isotherms to predict the amount of P needed to maintain that soil solution P level (Samadi, 2003). However, there is a scant published data available regarding the use of this technique for calcareous alkaline soils, as found in Pakistan.

Application of P fertilizers at the proper time tied with the best suited application method is of prime importance for attaining the highest yield potential in different arable crops (Rashid, 1994). Broadcasting, banding, point placement, split application, fertigation, and foliar application are among the methods of P application adopted under different cropping systems (Cisse and Amar, 2002). The lower PUE in Pakistan is mainly due to the use of broadcasting at seedbed preparation (Shah et al., 2006). Efficiency of applied P fertilizers can be improved by adopting appropriate methods of application. In our previous study with sandy loam soil, higher productivity in wheat tied to elevated PUE was observed in the band-placement technique of P compared with broadcasting (Rehim et al., 2012a). The high price of P fertilizers also points to a need to devise new methodologies to attain higher use efficiency (Twyford, 1994; Shah et al., 2006).

Integrated use of organic and mineral nutrients is the best move in nutrient management approaches for improving soil fertility status connected with higher crop yield (Sarwar, 2005). The synergetic effect of organic manure with inorganic fertilizers improves the efficiency of applied fertilizer and is more economical, as inorganic fertilizers are costly (Hussain et al., 1988). The use of farm manure (FM) as a source of nutrients for crop production has received attention for its role in sustainable crop productivity. The PUE can be improved significantly by integration of organic and inorganic fertilizer sources of P (Yamoah et al., 2002). For instance, inorganic P and fully decomposed FM at a 1:2 ratio mixed 12 h before application resulted in 30% higher PUE (Government of Pakistan, 2003). The application of FM improves soil organic matter, i.e. its microbial and physiochemical properties, leading to enhanced P nutrition in crop plants (Belay et al., 2001). Rehim et al. (2012) reported higher wheat output and PUE with the combined application of P and FM in sandy loam soil.

Keeping the aforementioned discussion in mind, it was hypothesized that wheat productivity and PUE could be improved by using better P application methods combined with application of FM. This field trial was designed to optimize the P levels, estimated by adjusted soil solution P levels according to the Freundlich model, and the application method to maximize wheat yield, PUE, and net economic return on calcareous soils with and without FM application.

2. Materials and methods

Wheat (*Triticum aestivum* L.) cultivar Inqulab-91 was used as the experimental material.

2.1. Experimental site description

This field experiment was carried out in Faisalabad, Punjab, Pakistan, during winter 2011/2012. The soil was quite uniform and calcareous ($CaCO_3$ >5%). The physicochemical analysis of the soil is given in Table 1. Climatic data from the growing season are given in Table 2.

2.2. Experimental details

The study was carried out using a randomized complete block design under factorial arrangements by keeping FM, application methods, and P levels in main plots, subplots, and sub-subplots, respectively. The entire experiment was replicated four times with plot size of 1.8 m × 4 m for the replications. Distance between the main plots was 1 m; between subplots it was 0.5 m. The five P rates, i.e. 0.00, 36.00, 61.00, 104.00, and 142.00 kg P_2O_5 ha^{-1}, used in the study were quantified according to the adjusted soil solution P rates of 0.00, 0.05, 0.10, 0.20, and 0.30 mg P L^{-1}. These levels were calculated by using the Freundlich model (Samadi, 2003). Phosphorus was applied through broadcasting, band-application, and top-dressing techniques. The experiment was conducted in two equal parts: for the first part, P application techniques and levels were used without FM, and for the second part, 300 kg ha^{-1} of fully decomposed FM (Rehim et al., 2012b) was added along with the above-mentioned P application techniques and levels.

Table 1. Soil physical and chemical properties.

Properties	Units	Sites
	0–30 cm	
EC_e	dS m^{-1}	2.3
pH_s		7.8
$CaCO_3$	%	5.6
Organic matter	%	0.8
Olsen P	mg kg^{-1}	7.7
Extractable K	mg kg^{-1}	140
Sand	%	56
Silt	%	22
Clay	%	23
Textural class	Sandy clay loam	

Table 2. Climate data of the experimental site during the study (2011/2012).

Month	Mean monthly temperature (°C)	Mean monthly relative humidity (%)	Total monthly rainfall (mm)
Nov. 2011	21.2	46.6	12.4
Dec. 2011	16.3	58.2	30.3
Jan. 2012	12.6	66.3	9.0
Feb. 2012	17.3	66.1	46.8
Mar. 2012	19.8	48.0	48.2
Apr. 2012	29.7	37.4	0.0

Source: Agricultural Meteorology Cell, Department of Crop Physiology, UAF, Faisalabad, Pakistan.

2.3. Application of the Freundlich model for computation of P doses

The P adsorption capacity of the soil was determined by shaking 2.5 g of soil with 25 mL of 0.01 M $CaCl_2$ containing P concentrations of 0, 5, 20, 40, 60, 80, 100, 200, 300, 400, and 500 µg P mL^{-1} prepared from KH_2PO_4 for 24 h at 20 °C. These soil solutions were filtered through Whatman No. 41 filter paper, and the ascorbic acid method (Murphy and Riley, 1962) was used for P concentration measurement; adsorption isotherms were built through the method of Rowell (1994). The amount of P adsorbed was estimated by the difference between P added and P remaining in the solution after P equilibrium was established. The adsorption data were fitted to the derived Freundlich equations (Samadi, 2003) to compute P fertilizer doses as follows:

$$X/m = K_f (EPC)^{1/n}$$

The linear form of the equation is log X/m = log K_f + 1/n (log EPC).

Here, X/m = amount of P adsorbed per unit of soil (µg g^{-1}),

EPC = equilibrium P concentration in soil solution (µg mL^{-1}),

K_f is the proportionality constant for the Freundlich equation (mg P kg^{-1}), and

1/n is an empirical constant expressed in L kg^{-1}.

The P doses computed by putting the adsorption data into the linear form of the derived Freundlich equation to achieve soil solution P levels of 0.00, 0.05, 0.10, 0.20, and 0.30 mg L^{-1} were 0, 16, 26, 45, and 61 kg P ha^{-1}. These were then converted to P_2O_5 (0, 36, 61, 104, and 142 kg ha^{-1}) by multiplying by 2.29.

2.4. Crop husbandry

Before seedbed preparation, 10 cm of irrigation was applied. At field capacity, the seedbed was prepared by plowing the soil two times followed by planking. The crop was sown on 10 November 2011 by using a single-row hand drill at the seed rate of 125 kg ha^{-1}, and row-to-row distance was maintained at 22.5 cm. There were eight rows 6 m in length in each plot; harvest data were taken from lengths of 4 m. Calculated levels of P together with 130 kg of nitrogen (N) and 65 kg of potassium (K) ha^{-1} were applied. Whole K and P along with half N were applied at seedbed preparation, while the remaining N was applied at first irrigation. Well-rotted FM mixed with P fertilizers was applied at the time of sowing. Overall 4 irrigations were applied to save the crop from moisture stress. The wheat crop was harvested at harvest maturity on 14 April 2012.

2.5. Observations recorded

Total numbers of productive tillers were counted from a unit area of 1 m^2 from three random selected points in each experimental unit and averaged. The average numbers of grains per spike were calculated from 20 randomly selected spikes. To estimate 1000-grain weight, five samples of 1000 grains from each experimental unit were counted, weighed, and averaged. Avoiding the border impact, grain and biological yields were determined from two central rows and then converted into t ha^{-1} accordingly (Rehim et al., 2012a, 2012b). Harvest index (%) was determined as the ratio between grain and biological yield expressed as a percentage.

Separate samples of 1 g of oven-dried grain and straw were taken for P analysis. Sample digestion was carried out by following standard methodology (Method 54a; US Salinity Laboratory, 1954). After digestion in a 50-mL volumetric flask, 5 mL of aliquot, 5 mL of ammonium vanadate (0.25%), and 5 mL of ammonium molybdate (5%) were added and the volume was made up. The spectrophotometer reading was calculated according to Rehim et al. (2012a, 2012b). At wheat harvest soil samples were analyzed for Olsen P (Olsen et al., 1954). Phosphorus uptake by grains and straw was calculated with the following equation:

$$P\ uptake\ (kg\ ha^{-1}) = \frac{P\ contents\ (\%)\ in\ plant\ part\ (dry\ matter) \times Yield\ (kg\ ha^{-1})}{100}$$

PUE was calculated by the following equation (Fageria et al., 1997):

$$PUE\,(\%) = \frac{\left[Total\ P\ uptake\,(kg\ ha^{-1})\ in\ fertilized\ plot\right] - \left[Total\ P\ uptake\,(kg\ ha^{-1})\ in\ control\ plot\right]}{P\ dose\ applied\,(kg\ ha^{-1})}$$

The grain protein content was calculated according to Chapman and Pratt (1961).

2.6. Statistical and economic analysis

The data were analyzed statistically by using the MSTAT-C computer program. The least significant difference (LSD) test ($P \leq 0.05$) was used to determine differences among means (Steel et al., 1997). The details of fixed and variable cost are represented in Table S1 (supplementary material). Due to the small size of plots, the grain yield was reduced to 10% to make the results comparable at the farm level, as suggested by Byerlee (1988). Total gross income was computed keeping in view the existing market price of wheat grains and straw locally. Total net field income was calculated as the difference between the gross income and total cost (including both fixed and variable costs) (Byerlee, 1988). Benefit/cost ratio (BCR) was calculated using gross income and total expenses according to Shah et al. (2013).

3. Results

Phosphorus rates and application techniques affected grain yield and related traits significantly ($P \leq 0.05$), both with and without FM (Table 3). Band-placement of P showed maximum productive tillers, grains spike^{-1}, 1000-grain weight, and grain yield compared to broadcasting and top-dressing, both with FM application and without application (Table 3). Meanwhile, P application at 104 kg P_2O_5 ha^{-1} showed maximum productive tillers, grains spike^{-1}, 1000-grain weight, and grain yield that was statistically at par with 142 kg P_2O_5 ha^{-1}, both with and without FM application; the control (0.00 kg P_2O_5 ha^{-1}) performed poorly in this regard (Table 3). However, FM application substantially improved the yield and related traits of wheat under different levels and methods of P application (Table 3).

Band-placement of P showed maximum straw and biological yield compared with broadcasting and top dressing, both with and without FM application (Table 4). Likewise, P application at 104 kg P_2O_5 ha^{-1} showed maximum straw and biological yield that was statistically at par with 142 kg P_2O_5 ha^{-1} only under FM application; the control (0.00 kg P_2O_5 ha^{-1}) performed poorly in this regard (Table 4). However, FM application considerably increased the straw and biological yield under different levels and methods of P application (Table 4). Band-placement of P and its application at 104 kg P_2O_5 ha^{-1} delivered the maximum harvest index, which was further improved by

Table 3. Effect of various levels and techniques of phosphorus application on yield and yield-related parameters of wheat under varying levels of FM application.

Treatments	Productive tillers (m^{-2})		Mean	Number of grains spike^{-1}		Mean	1000-grain weight (g)		Mean	Grain yield (mg ha^{-1})		Mean
FM (kg ha^{-1})	0	300		0	300		0	300		0	300	
Methods of P application												
Broadcasting	270.897 c*	275.53 bc	273.2 b	32.72 c	36.49 b	34.61 b	38.64 ab	39.00 ab	39.11 b	3.14 c	3.44 b	3.29 c
Band-placement	280.27 b	287.27 a	283.77 a	33.95 c	37.84 a	35.90 a	39.68 ab	40.82 a	40.26 a	3.37 b	3.71 a	3.54 a
Top dressing	273.87 bc	281.40 ab	277.63 b	32.89 c	36.59 b	34.74 b	38.32 b	39.98 ab	39.31 b	3.19 c	3.63 a	3.41 b
LSD at 5%	7.26		5.51	1.20		1.101	2.34		0.85	0.15		0.112
P levels (kg ha^{-1})												
0	238.33 f	247.67 ef	243 d	28.00 g	31.50 ef	29.75 d	36.37 d	35.87 d	36.12 d	2.30 e	2.43 de	2.37 e
36	255.11 e	263.44 de	259.28 c	30.14 fg	32.94 de	31.54 c	39.21 bc	37.26 cd	38.23 c	2.86 d	3.44 c	3.15 d
61	279.33 cd	286.56 bc	282.94 b	34.83 cd	37.84 b	36.33 b	41.03 ab	39.08 bc	40.10 b	3.44 c	3.67 bc	3.51 c
104	301.00 ab	305.89 a	303.44 a	36.70 bc	41.90 a	39.30 a	42.83 a	41.44 a	42.14 a	4.00 ab	4.34 a	4.17 a
142	301.22 ab	303.44 a	302.33 a	36.28 bc	40.71 a	38.49 a	41.73 a	40.79 ab	41.26 a	3.66 bc	4.08 ab	3.87 b
LSD at 5%	16.26		7.12	2.46		1.42	2.06		1.10	0.45		0.15
FM mean	275 b	281.4 a		33.19 b	36.98 a		38.89 b	40.24 a		3.24 b	3.60 a	
LSD at 5%	4.50			0.899			0.69			0.091		

Means sharing the same letter within a column do not differ significantly at a 5% level of probability.

FM application (Table 4). Broadcasting of P led to higher Olsen P compared to band-placement, which showed lower Olsen P, both with and without FM application (Table 4). Similarly, maximum Olsen P contents were observed at the high rate of P under both FM application conditions (Table 4). Moreover, band-placement of P and higher levels of P application resulted in higher grain protein content, which was further improved by FM application (Table 4).

Phosphorus rates and application techniques significantly ($P \leq 0.05$) affected the P concentration and uptake by wheat grain and straw and PUE under both levels of FM application (Table 5). Compared with broadcasting and top-dressing, banding of P substantially improved the P concentration and uptake by wheat grain and straw and PUE under both levels of FM application; however, FM application further provoked P concentration and uptake by wheat grain and straw and PUE (Table 5). Nonetheless, P concentration and uptake by wheat grain and straw and PUE was gradually enhanced with increasingly higher levels of applied P, either with FM application or without. However, FM application further provoked P concentration and uptake by wheat grain and straw and PUE at each level of applied P (Table 5).

Although broadcasting of P provided the minimum cost of production, band-placement of P provided higher net returns and BCR due to a substantial improvement in gross income under both levels of FM addition (Table 6). Added P at 104 kg ha^{-1} provided maximum net income and BCR followed by P application at the rate of 61 kg ha^{-1}, with and without FM application (Table 6). Moreover, added FM further improved the net returns and BCR under varying levels and methods of P application (Table 6).

4. Discussion

Results of this field study pointed out that wheat productivity, PUE, and net economic returns can be improved by wise application of P using band-placement coupled with FM application (Tables 3 and 4). Higher grain yield was attained with P application at 104 kg P_2O_5 ha^{-1}, and the further addition of P after this rate reduced the wheat yield (Table 3), demonstrating that overapplication of P might be toxic and impact yield negatively. However, optimal P supply (104 kg P_2O_5 ha^{-1}) enhanced wheat productivity by improving the entire yield and yield parameters (Table 3). The improvement in productive tillers with added P was due to its role in initial growth (Cook and Veseth, 1991). Daniel et al. (1998) stated the same findings in wheat with added P. Phosphorus application also regulates the energy storage and transfer in cells. Moreover, P is a structural component of various essential compounds, and it regulates the meristematic activities in newly emerging roots and helps in uptake of N and essential nutrients. On the other hand, deficiency of P changes the usual pattern of tiller appearance, roots, and plant growth (Daniel et al., 1998), hence reducing better crop yields (Table 3). Notable yield boost in wheat with added P is well documented (Alam et al., 2003; Rehman et al., 2005; Rahim et al., 2010; Rehim et al., 2012a).

Table 4. Effect of various levels and techniques of phosphorus application on straw and biological yield, harvest index (HI), Olsen P, and protein contents of wheat under varying levels of FM application.

Treatments	Straw yield (t ha^{-1})		Mean	Biological yield (t ha^{-1})		Mean	Harvest index (HI)(%)			Olsen P (mg L^{-1})		Mean	Grain protein contents (%)		
FM (kg ha^{-1})	0	300		0	300		0	300	Mean	0	300		0	300	Mean
Methods of P application															
Broadcasting	5.04 c	5.11 bc	5.08 b	8.18 d	8.55 c	8.37 c	38.15 c	40.00 ab	39.08 a	8.90 b	9.45 a	9.18 a	10.51 e	11.63 c	11.07 b
Band-placement	5.19 ab	5.30 a	5.25 a	8.57 c	9.02 a	8.79 a	39.93 bc	40.83 a	39.88 a	8.37 e	8.38 e	8.38 c	11.12 d	12.15 a	11.63 a
Top dressing	5.11 bc	5.18 a–c	5.15 b	8.30 d	8.81 b	8.55 b	38.16 c	40.87 a	39.52 a	8.58 d	8.70 c	8.64 b	10.32 f	11.89 b	11.11 b
LSD at 5%	0.14		0.089	0.17		0.148	1.46		0.96	0.012		0.0119	0.16		0.097
P levels (kg ha^{-1})															
0	4.31 g*	4.10 g	4.21 e	6.62 e	6.54 e	6.58 e	34.73 e	37.04 de	35.89 d	3.04 i	4.17 h	3.61 e	8.47 g	9.15 f	8.82 e
36	4.83 f	5.10 e	4.97 d	7.69 d	8.55 c	8.13 d	37.14 de	40.22 bc	38.68 c	6.03 f	5.48 g	5.76 d	9.43 f	10.74 e	10.09 d
61	5.16 de	5.37 cd	5.27 c	8.50 c	9.05 b	8.78 c	39.30 cd	40.63 a–c	39.97 b	8.51 e	8.75 d	8.63 c	10.57 e	12.28 c	11.42 c
104	5.75 a	5.79 a	5.77 a	9.80 a	10.10 a	9.95 a	40.85 a–c	43.03 a	41.94 a	11.09 c	11.05 c	11.07 b	11.65 d	13.50 a	12.57 b
142	5.47 bc	5.66 ab	5.57 b	9.14 b	9.74 a	9.44 b	40.04 bc	41.91 ab	40.98 ab	14.43 b	14.76 a	14.60 a	13.16 b	13.78 a	13.47 a
LSD at 5%	0.22		0.114	0.41		0.192	2.55		1.24	0.41		0.015	0.28		0.126
FM mean	5.12 b	5.20 a		8.35 b	8.80 a		38.41 b	40.56 a		8.62 b	8.85 a		10.65 b	11.89 a	
LSD at 5%	0.073			0.121			0.79			0.009			0.079		

Means sharing the same letter within a column do not differ significantly at a 5% level of probability.

Table 5. Effect of various levels and techniques of phosphorus application on P concentration and uptake of grain and straw and PUE of wheat under varying levels of FM application.

Treatments	P concentration in grain (%)		Mean	P concentration in straw (%)			P uptake in grain (kg ha⁻¹)		Mean	P uptake in straw (kg ha⁻¹)			PUE (%)		Mean
FM (kg ha⁻¹)	0	300		0	300	Mean	0	300		0	300	Mean	0	300	
Methods of P application															
Broadcasting	0.13 d	0.15 c	0.15 c	0.10 bc	0.09 c	0.0933 b	4.44 e	5.70 c	5.07 c	4.91 b	4.73 b	4.82 b	4.21 d	6.46 c	5.33 c
Band-placement	0.16 b	0.17 a	0.17 a	0.11 a	0.09 bc	0.0985 a	5.98 c	7.04 a	6.52 a	5.58 a	5.07 b	5.32 a	6.38 c	8.94 a	7.66 a
Top dressing	0.15 c	0.16 b	0.16 b	0.09 b	0.09 c	0.0914 b	5.09 d	6.54 b	5.82 b	4.93 b	4.80 b	4.87 b	4.74 d	7.79 b	6.27 b
LSD at 5%	0.038		0.0029	0.036		0.0031	0.29		0.19	0.29		0.199	0.45		**0.36**
P levels (kg ha⁻¹)															
0	0.10 ef*	0.08 f	0.093 e	0.06 cd	0.05 d	0.060 d	2.27 h	2.11 h	2.19 e	2.88 fg	2.20 h	2.55 e	0.00 g	0.00 g	0 e
36	0.08 f	0.10 d–f	0.097 d	0.06 cd	0.05 d	0.060 d	2.55 h	3.68 g	3.12 d	3.27 f	2.63 gh	2.59 d	1.86 f	6.67 e	4.27 d
61	0.13 c–e	0.14 cd	0.137 c	0.09 bc	0.07 cd	0.086 c	4.39 f	5.24 e	4.81 c	4.98 d	4.09 e	4.53 c	6.90 e	8.87 c	7.89 c
104	0.15 bc	0.19 b	0.175 b	0.12 ab	0.11 ab	0.119 b	6.19 d	8.47 c	7.33 b	6.99 c	6.82 c	6.91 b	7.72 d	10.94 b	9.33 b
142	0.28 a	0.31 a	0.297 a	0.13 a	0.15 a	0.145 a	10.47 b	12.66 a	11.56 a	7.58 b	8.58 a	8.08 a	9.07 c	12.20 a	10.63 a
LSD at 5%	0.041		0.0038	0.041		0.0039	0.047		0.25	0.51		0.258	0.79		0.46
	0.15 b	0.17 a		0.098 a	0.09 b		5.18 b	6.43 a		5.14 a	4.87 b		5.11 b	7.73 a	
	0.0024			0.0025			0.16			0.16			0.29		

*Means sharing the same letter within a column do not differ significantly at a 5% level of probability.

Table 6. Effect of various levels and techniques of P application on net income and benefit-to-cost ratio (BCR) of wheat under varying levels of FM application.

Treatments	Total expenses (*Rs ha⁻¹)		Gross income (Rs ha⁻¹)		Net income (Rs ha⁻¹)		BCR	
FM (kg ha⁻¹)	0	300	0	300	0	300	0	300
Methods of P application								
Broadcasting	80,936	82,436	114,360	123,640	33,424	41,204	1.41	1.50
Band-placement	81,936	83,436	121,860	132,500	39,924	49,064	1.49	1.59
Top dressing	81,936	83,436	116,140	129,620	34,204	46,184	1.42	1.55
P levels (kg ha⁻¹),								
0	69,800	71,300	86,240	89,300	16,440	18,000	1.24	1.25
36	75,760	77,260	105,120	123,600	29,360	46,340	1.39	1.60
61	79,760	81,260	123,840	131,580	44,080	50,320	1.55	1.62
104	86,640	88,140	143,160	153,200	56,520	65,060	1.65	1.74
142	92,720	94,220	131,680	145,040	38,960	50,820	1.42	1.54

*Rs: Pakistani rupee. 1 US$ = Rs 104.75 (March 2016).

Phosphorus application by band-placement ensures well-executed placement compared with other methods of P application. Band-placement of P creates close contact between roots and P-enriched soil. Moreover, in the case of band-placement, P makes less contact with soil particles. This contact is partially responsible for precipitation, fixation, or retention of P fertilizer; this ultimately reduced P uptake (Shah et al., 2006; Rehim et al., 2012b). The higher available P supply improved the uptake of other mineral nutrients and ensured optimum cell growth, reproduction, photosynthesis, and transformation of sugars and starches. Recently, Rehim et al. (2012a) reported better grain yield with notable improvement in yield parameters in wheat by band-placement of P compared to broadcasting.

The higher grain and straw P contents noted at higher levels of P application might be due to the elevated P concentration in the soil aqueous phase that was plant-available (Table 3). Similarly, adsorption of P is augmented at a high rate of P application as plants can freely use 8%–33% of applied P during the first crop season, and the remaining portion is fixed, which increases Olsen P (Hussein, 2009). A similar finding was noted by Rahim et al. (2010), who stated that incessant application of P showed a notable rise in soil solution P. However, the high PUE noted at the lower P level could be the outcome of strong competition among roots and may thus point to effective utilization of applied P. Hilton et al. (2010) reported that at lower doses of P, plants retain most of the applied P through interception by growing their roots and occupying the adjacent soil volume, therefore enhancing the PUE. Similarly, at higher levels of applied P, plants utilized a smaller fraction of the added P, which resulted in low PUE (Rehim et al., 2012a). With every added increased dose of P fertilizer, grain protein content was substantially improved (Table 4), which might be due to better N uptake with the increasing P rate.

Newly developing roots obtained close contact with P-enriched soil through nearby fertilizer granules under band-placement of P, which eventually enhanced the P uptake and improved the straw and grain P contents (Linkohr et al., 2002; Ticconi et al., 2004). However, in the case of band-placement, P adsorption is at a minimum due to reduced contact with soil particles as compared to the broadcasting technique. The higher PUE noted in band-placement might be due to reduced fixation and efficient utilization of added P due to the small soil-to-fertilizer ratio in band-placement, as P sorption maxima depend on the ratio of soil to applied P.

Nonetheless, the addition of FM augmented wheat productivity and PUE under different levels and methods of application used (Tables 3–5). The addition of FM can improve the soil organic matter status, soil physiochemical properties, and soil microbial activities and thus improves nutrient uptake and use efficiencies of plants, including PUE (Belay et al., 2001; Rehim et al., 2012b). Moreover, the addition of FM also improves the supply of micronutrients. Due to the balanced supply of nutrients under FM application, wheat productivity improved through prominent expansion of all yield-related parameters and improved PUE (Tables 3–5). Hence, the PUE improved radically when organic and inorganic sources of phosphorus were used together (Yamoah et al., 2002). Although the organic matter content of the experimental field was very low (0.8%) (Table 1), FM application did not have any effect on P dose in improving wheat productivity or PUE under all application methods (Tables 3 and 4). This might be due to the very small dose, i.e. 300 kg ha^{-1}, of FM used in this study, which was not enough to influence P dose.

Commercial adoption of any new innovation/technique at farm level depends on its economic feasibility, which can be judged by net gains and BCR. Higher net income and BCR from P application at 104 kg P_2O_5 ha^{-1} and the band-placement technique of P application coupled with FM resulted in better grain yield (Table 3) due to a more proficient exploitation of applied fertilizer. Therefore, the band-application of P at 104 kg P_2O_5 ha^{-1} must be used along with FM to improve wheat yield, PUE, net income, and BCR of wheat.

In conclusion, soil testing and the Freundlich model should be used to determine P needs of different soils and crops, as it accounts for the readily available soil solution P. In this field study, wheat productivity was increased radically by adding P, and the optimal dose for sandy clay loam calcareous soil was 104 kg P_2O_5 ha^{-1}. Band-placement is the better technique of P application to enhance its use efficiency. Moreover, FM application helps to improve the productivity and PUE of wheat under different levels and methods of P application. In order to obtain higher wheat output and PUE in sandy clay loam soil, band-placement of P at 104 kg P_2O_5 ha^{-1} (0.20 mg P L^{-1} soil solution) along with 300 kg ha^{-1} well-decomposed FM is best.

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Table S1. Details of fixed and variable costs of wheat grown with different P levels and application methods, with and without FM application.

Treatments	Variable cost due to P level and application method (Rs ha^{-1})		Fixed cost (*Rs ha^{-1})								
	No FM	FM	Fertilize except P	Land rent	Seedbed preparation	Seed	Irrigation	Labor	Harvesting	Threshing	Total fixed costs
P application methods											
Broadcasting	11,136	12,636	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
Band-placement	12,136	13,636	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
Top dressing	12,136	13,636	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
P levels (kg ha^{-1}),											
0	0	1500	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
36	5960	7460	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
61	9960	11,460	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
104	16,840	18,340	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800
142	22,920	24,420	16,400	24,000	6000	3850	6000	3550	5000	5000	69,800

FM = Farm manure.

*Rs: Pakistani rupee. 1 US$ = Rs 104.75 (March 2016).