PHOSPHORUS REQUIREMENT OF WHEAT USING MODIFIED FREUNDLICH MODEL IN RASULPUR SOIL SERIES

Obaid-ur-Rehman*, A.M. Ranjha**, M.A. Gill** and S.M. Mehdi*
*Soil Salinity Research Institute, Pindi Bhattian.
**University of Agriculture, Faisalabad.

A field experiment was conducted on Rasulpur soil series (Typic Camborthids) to determine P requirement of wheat for obtaining 95 % relative yield. Site selection criteria were calcareousness and P deficiency. Phosphorus sorption isotherms were constructed to study the behavior of soil to phosphate application by adding 0, 5, 10, 15, 20, 40, 60 and 80 μg P mL^{-1} and modified Freundlich equation was constructed. The parameters **a** (amount adsorbed in μg g^{-1}) and **b** (buffer capacity in mL g^{-1}) were estimated by regression of the logarithmic form of the data obtained from the adsorption isotherms. Theoretical doses of P (mg kg^{-1} soil) were calculated from this equation to develop P levels in the soil solution under field conditions which were 0.01, 0.02, 0.03, 0.04, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40 and 0.50 with native solution P level as control with and without N and K. Wheat crop was grown in the randomized complete block design with three replications. Maximum wheat grain and straw yield of 3.37 and 3.50 Mg ha^{-1}, respectively was recorded at solution P level of 0.20 mg P L^{-1}. Phosphorus concentration in wheat grain and straw was 0.410 and 0.138 % which was found at solution P level of 0.40 mg P L^{-1}, respectively. External solution P requirement was 0.146 mg P L^{-1} and internal P requirement was found 0.289 % for obtaining 95 % relative yield of wheat.

Key words: Phosphorus sorption isotherms, modified Freundlich model, wheat yield, P concentration, external and internal P requirement.

INTRODUCTION

Phosphate availability in Pakistani soils is reduced due to alkaline soil conditions, high calcium contents and a large amount of calcium saturated clay. To maintain a given level of available phosphorus, it is necessary to apply adequate quantities of phosphatic fertilizers into the soil (NFDC, 2003). High P sorption is considered as a constraint to economic utilization of P as more than 80 % of fertilizer applied P will be immediately unavailable for plant uptake either due to adsorption, precipitation or both in soil (White, 1982). Soil solution P is an immediate source of P for plant uptake (Holford, 1989). Ahmad *et al.* (2003) conducted a survey on evaluation of nutrient status in the rice growing area of Punjab and observed that the available phosphorus ranged from 0.3-12.6 mg kg^{-1} with an average of 5.89 mg kg^{-1} soil. Soils vary greatly in the amount of P required to provide an adequate supply of available P for plant and plants also vary in their P requirement for optimal growth (Vanderzaag *et al.*, 1979). The literature suggests that optimum solution P concentration (0.2 mg L^{-1}) provides P adequately for many crops if it is continuously maintained in the medium (Beckwith, 1965). The Freundlich equation is often considered to be purely empirical in nature but has been used extensively to describe the adsorption of phosphate by soils (Aslam *et al.*, 2000; Arshed *et al.*, 2000; Javid and Rowell, 2002; Chaudhry *et al.*, 2003). Using P sorption approach, P requirement of several crops has been determined under a variety of soil and climatic conditions (Fox, 1981; Vanderzaag *et al.*, 1979; Memon *et al.*, 1992 Hassan *et al.*, 1993 & 1994). This approach has an advantage over conventional method of soil testing since it integrates P intensity, capacity and buffering capacity aspects of the soil which play important role in controlling the P flux to most of the growing plants. Moreover, fertilizer requirement can be estimated directly from P sorption curves. Chaudhry *et al.* (2003) determined P requirement of maize by using sorption isotherm and fitted data in Langmuir and modified Freundlich equations and found that 22-67 mg P kg^{-1} was required to maintain 0.2 mg P L^{-1} soil solution in different soil series. According to the scale given by Juo and Fox (1977), the data from P sorption studies indicated that the soils of Pakistan had a low P sorption capacity. The addition of 50-100 kg P_2O_5 ha^{-1} in many cases increased the level of solution P to the desired level for optimal production. Nisar (1988) reported the result of wheat grown at four locations in Hafizabad, Gujranwala, Lyallpur and Sultanpur soil series. Phosphorus in soil solution at 95 % maximum yield varied significantly among these soils. The P in solution for Lyallpur, Gujranwala, Hafizabad and Sultanpur series were found to be 0.09, 0.052, 0.26 and 0.90 ug mL^{-1}, respectively and the corresponding P requirement for 95 % of maximum yield were 75, 92, 114 and 150 kg P_2O_5 ha^{-1} for these soil series, respectively. Similarly, Memon *et al.*, (1991) reported that the P requirement of wheat grown on calcareous soils of Pakistan was 0.032 mg L^{-1} for 95 % yield as determined from a composite yield response curve. The nutrient requirement of a crop can be expressed in several ways. The term "internal nutrients requirement" may delineate the minimum uptake of nutrient (a quantity factor in plant nutrition) that is associated with a specified yield. The internal requirement can also be defined as the concentration of nutrient in the plant (an intensity factors in plant nutrition) that is associated with near maximum yield usually named as the "Critical concentration" (Fox, 1981). Crops have external requirements too. External phosphorus requirement of crop may be defined as the maximum concentration of P in soil solutions equilibrated with soils associated with near maximum attainable yield of crop. The quantity of nutrient frequently taken up is of great significance if it is considered in relation to the capacity of the soil to hold nutrients; thus both the internal and the external requirement can be expressed in terms of P quantity, intensity and capacity factor. Fox (1981) demonstrated that the external P requirement is not a single valued constant that holds for all conditions and suggested that the concentration of P in dilute salt solution is a useful indicator of the P nutrition of crops and that the external P requirement might be widely applied in conjunction with P sorption curves to estimate P fertilizer requirement. The P sorption approach provides a possible mean and has been advocated as a rational basis for estimating both the need for P and amount for a given soil crop combination (Vanderzaag *et al.*, 1979; Fox *et al.*, 1989). Keeping all this in view, a study was planned in the Rasulpur soil series to determine phosphorus adsorption capacity of the soil and then computing P doses for field application to determine external and internal P requirement of wheat.

MATERIALS AND METHODS

Soil

A field experiment was conducted at the research farm of Soil Salinity Research Institute, Pindi Bhattian which is a rice growing tract of the Punjab. Representative composite soil samples were collected from 0-20 cm depth with the help of an auger. Soil physical and chemical properties were determined using methods described in Handbook No. 60 (U.S. Salinity Lab. Staff, 1954). Lime and Particle size analyses were determined by the method of Moodie *et al.* (1959) and available phosphorus was measured by the procedure as given by Watanabe and Olsen (1965).

P Sorption

Phosphorus sorption isotherms were constructed by the methodology of Rowell (1994). To 2.5 g sample of soil, 25 ml of 10 mM $CaCl_2$ solution containing a series of phosphate concentrations was added. The initial concentration of P in solution ranged from 0-80 µg P mL^{-1} (0, 5, 10, 15, 20, 40, 60 and 80). The soils were shaken on end over end shaker for 24 h. The samples were filtered through a Whatman No. 42 filter paper. The P concentration in the final solution was determined by the method of Murphy and Riley (1962). The difference between amount of P in solution before and after equilibrium was taken as the amount of P sorbed (Nair et al., 1994). The sorption isotherms were examined by modified Freundlich equations proposed by Le Mare (1982). The simple form of the Freundlich model was proposed by Le Mare (1982) as follows:

$$\mathbf{P = a\,C^{b}}$$

Where **P** is quantity of sorbate (µg) per unit weight (g) of adsorbent, **C** is equilibrium solution concentration (µg P mL^{-1}) of the adsorbate, **a** is the amount of P adsorbed (µg g^{-1}) when the concentration C is 1 µg mL^{-1} and b (mL g^{-1}) is the buffer power defined by the slope of the sorption curve at the point where P / C = 1 (mL g^{-1}). The value of **P / C** varies between soils.

The modified Freundlich model used to describe the soils in this work is as follows:

$$\mathbf{P = a\,C^{b/a}}$$

A = anti **ln** of intercept (from linear form or regression equation of the model)

B = **slope** x **a** (from linear form or regression equation of the model)

The main advantage of this equation is that **a** and **b** are the amount of P adsorbed and the buffer capacities, respectively at the same point on the curve where **C** = 1 µg mL^{-1} and this point is the same for all the soils. The parameters **a** and **b** were estimated by regression of the logarithmic form of the data obtained from adsorption isotherms. Theoretical doses phosphatic fertilizers to develop P levels in soil solutions (0.01, 0.02, 0.03, 0.04, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40 and 0.50 with native solution P level as control with and without nitrogen and potash) under field conditions were calculated from this equation (Table 1).

Table 1. Computed P doses to be applied in the field.

Sr. No.	P in soil solution (mg L^{-1})	P (mg kg^{-1} soil) to be added	P_2O_5 (kg ha^{-1}) to be added
1	Native (0 NK)	0	0
2	Native (+ NK)	0	0
3	0.01	8.23	37.69
4	0.02	11.38	52.12
5	0.03	13.76	63.02
6	0.04	15.74	72.09
7	0.05	17.48	80.06
8	0.10	24.17	110.70
9	0.15	29.22	133.83
10	0.20	33.43	153.11
11	0.25	37.11	169.96
12	0.30	40.42	185.12
13	0.40	46.25	211.83
14	0.50	51.34	235.14

Field Trial

Wheat (*Triticum aestivum* L.) crop cv. Inqulab-91 was sown with seed rate of 125 kg ha^{-1} after treating the seed with benlate @ 100 g per 40 kg wheat seed. Half of the recommended nitrogen (70 kg ha^{-1}) and potassium (K_2O) @ 70 kg ha^{-1} along with phosphorus (P_2O_5) doses calculated from modified Freundlich model for developing soil solution P were applied at sowing in the form of urea, potassium sulphate and single super phosphate, respectively. Second half of nitrogen was applied at first irrigation. The crop was harvested at ground level at maturity. Grain and straw yield data were recorded by harvesting the whole plot. Grain and straw samples were analyzed for P concentration.

The yield representing each phosphorus level was expressed as percentage of maximum yield of the experiment. The percentage yield, also termed as relative yield, was expressed as the yield with test nutrient added as percentage of maximum yield. The relative yield is a measure of the yield response to a single nutrient when other nutrients are supplied adequately but not in excessive amount. It is calculated as

$$\text{Relative yield} = \frac{\text{Threshold yield for x} \times 100}{\text{Plateau yield for x}}$$

Where

Threshold yield = Yield at zero level of x

Plateau yield = Point of maximum response to x

x = Rate of nutrient (P) applied.

Relative yield (%) was plotted against soil solution P level and P concentration (%) in grain to determine the external and internal P requirement of wheat from the regression equation. All the parameters (grain, straw, P concentration) were statistically analyzed using method as described in Steel and Torrie (1980).

RESULTS AND DISCUSSION

All the physical and chemical characteristics of the soil used in this study are given in table 2. The soil used was non-saline, alkaline in nature, having clay content of 12 % and was sandy loam in texture. Calcium carbonate content was 5.15 % indicating that soil was moderately calcareous. The soil was deficient in organic matter and available P but medium in extractable K.

Freundlich plot of sorption data

After constructing the P adsorption isotherm (Fig. 1), the data was subjected to examine the fitness of modified Freundlich equation. The linear plot of the modified Freundlich equation presented in Fig. 2 and parameters of the equation [amount adsorbed (**a**), buffer capacity (**b**) mL g^{-1} and correlation coefficient (r^2)] are presented in table 3. The buffer capacities (**b**) of the soil was 33.65 mL g^{-1} and the amount of P adsorbed (**a**) was 71.91 µg g^{-1}. The goodness of the fit of the model was ascertained by looking at the r^2 value (0.91) indicate high conformity of the adsorption data with the modified Freundlich model. The linearization transformation of data showed that the plot was linear.

Table 2. Original soil analysis

Determinant	Units	Values
Sand	%	70
Silt	"	18
Clay	"	12
Textural class	-	Sandy Loam
Sub group	-	Typic Camborthid
Series		Rasulpur
pH_s	-	7.91
EC_e	dS m^{-1}	0.92
TSS	me L^{-1}	9.2
Ca^{2+}+ Mg^{2+}	"	5.10
Na^+	"	3.24
SAR	(mmol $L^{-1})^{0.5}$	1.13
CO_3^{2-}	me L^{-1}	-
HCO_3^-	"	1.2
Cl^-	"	2.7
SO_4^{2-}	"	5.3
$CaCO_3$	%	5.15
Organic matter	"	0.44
Olsen-extractable P	mg kg^{-1}	4.35
Extractable K	"	99

Table 3. Phosphorus sorption parameters of the Freundlich model

Soil	Amount adsorbed (a) µg g^{-1}	Buffer capacity (b) mL g^{-1}	Correlation coefficient (r^2)	No. of values (n)
Rasulpur	71.91	33.65	0.91	8

Generally the Langmuir model works under narrow P concentrations while Freundlich model seems fit at medium and high equilibrium P concentrations (Probert, 1983). The value of the exponent was found < 1 (Table 3) which relates to the characteristics of the adsorbent (soil or $CaCO_3$). The findings are in agreement with those of Kuo and Lotse (1974) and Chaudhry *et al.* (2003) who reported that exponent of the Freundlich equation was independent of the time and temperature and the values depended on solution P concentration.

Since the Freundlich adsorption equation was derived empirically, its parameters **a** and **b** have been considered of no use for practical purposes. Despite this, it was proposed that **a** could be considered as a capacity factor implying that a soil having a larger **a** value has larger adsorbing capacity than a soil having smaller **a** value. For practical purposes, the **a** value estimated in table 3 may be used to differentiate soils having different P adsorption capacities. The larger **b** values have larger curvature of the adsorption isotherm and for **b** = 1, the isotherms would be a straight line. Using the P adsorption parameters, the Freundlich plot equation was formulated (Table 4) on the basis of these values. Fitter and Sutton (1975) and Rathowsky (1986) reported similar observations.

Table 4. Modified Freundlich model

Soil	Modified Freundlich equation	
	Model form	Linear form
	$P = a\ C^{b/a}$	
Rasulpur	$P = 71.00\ C^{0.468}$	Y = 0.468 x + 4.2755

Computed P doses to be applied in the field

In the present study, the Freundlich model conformed to the observed adsorption data over medium range of equilibrium concentration. The Freundlich parameter **a** was used to be a practically useful parameter in summarizing the adsorption properties of the soil over wide range of equilibrium concentrations. Model form of modified Freundlich equation was used for computing P fertilizer quantities to develop the soil solution P level upto 0.01, 0.02, 0.03, 0.04, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40 and 0.50 mg L^{-1} i.e.,

$P = a\ C^{b/a}$

$\text{Log } P = \text{Log } a + b/a \text{ Log } C$

The P quantities computed as mg P kg^{-1} soil will be multiplied with 2 x 2.29 to get kg P_2O_5 ha^{-1} as described in table 1.

Wheat grain and straw yield (Mg ha^{-1})

Results regarding wheat grain and straw yield are depicted in table 5. The data revealed that maximum wheat grain yield (3.37 Mg ha^{-1}) was obtained at solution P level of 0.20 mg P L^{-1} which was developed by adding 153.11 kg P_2O_5 ha^{-1}. There was a progressive increase in yield with P application at lower or medium levels but at the higher levels of solution P, the yields were at par. This means that wheat responded differently to the solution P but response to the higher doses (> 0.30 mg P L^{-1}) was not observed. Similar results were also obtained by Saeed *et al.* (1992), Patal *et al.* (1997), Sharma and Singh (1998), Amrani *et al.* (1999) and Tomar *et al.* (1999). Similarly straw yield also increased at the same soil solution P levels and the trend was almost same as was seen in the case of grain yield. Maximum straw yield of 3.50 Mg ha^{-1} was noted at soil solution P level of 0.20 (153.11 kg P_2O_5 ha^{-1}). Minimum straw yield was recorded in the control plots where no fertilizer was added. The reason for this might be poor tillering in control plots which increased significantly with the application of P fertilizer and building solution P levels. Khattak and Iqbal (1992) also found similar results for maize crop.

Table 5. Wheat grain and straw yields (Mg ha^{-1}) and P concentration (%).

Solution P (mg L^{-1})	Grain yield	Straw yield	P (%) in grain	P (%) in straw
Native(0 NK)	1.09H	1.22H	0.107H	0.013H
Native(+ NK)	1.54G	1.67G	0.127H	0.017H
0.01	2.09F	2.21F	0.160G	0.023GH
0.02	2.42E	2.57E	0.173G	0.027GH
0.03	2.50E	2.63E	0.203F	0.038FG
0.04	2.73D	2.85D	0.220F	0.047EF
0.05	2.94C	3.07C	0.257E	0.059E
0.10	2.79CD	2.92CD	0.283D	0.077D
0.15	3.25B	3.38B	0.287D	0.088D
0.20	3.37AB	3.50AB	0.317C	0.110C
0.25	3.32AB	3.44AB	0.320C	0.123BC
0.30	3.35AB	3.49AB	0.377B	0.127B
0.40	3.41AB	3.55AB	0.410A	0.138AB
0.50	3.46A	3.59A	0.410A	0.147A
LSD	0.1673	0.1678	0.0239	0.0135

Means sharing same letters are statistically at par at 5 % level of probability.

Phosphorus concentration (%) in wheat grain and straw

Data regarding P concentration of wheat grain depicted in Table 5 reveal that maximum P concentration (0.41 %) was observed when solution P level of 0.40 mg L^{-1} was developed by adding 46.25 mg P kg^{-1} soil. This means that the soil was coarse textured and maximum P concentration was observed at low solution P level. Minimum P concentration of 0.11 % was determined in control plots. Duivenbooden *et al.* (1996) also reported P concentration in wheat grain between 0.25 – 0.49 %. Similarly, the data also revealed that maximum P concentration of 0.14 % was recorded (like P concentration in grain) at solution P level of 0.40 mg L^{-1} which was obtained by adding 46.25 mg P kg^{-1} soil. However, minimum P concentration 0.013 % was observed in plots receiving no fertilizer. It is an established fact that low P concentration in straw than grain is due to more P translocation to the grain in the reproductive stage. Duivenbooden *et al.* (1996) also reported P concentration in wheat straw between 0.03 - 0.08 %.

Phosphorus requirement of wheat

The P requirement of wheat crop was determined on the basis of 95 % of the maximum yield. The fertilizer

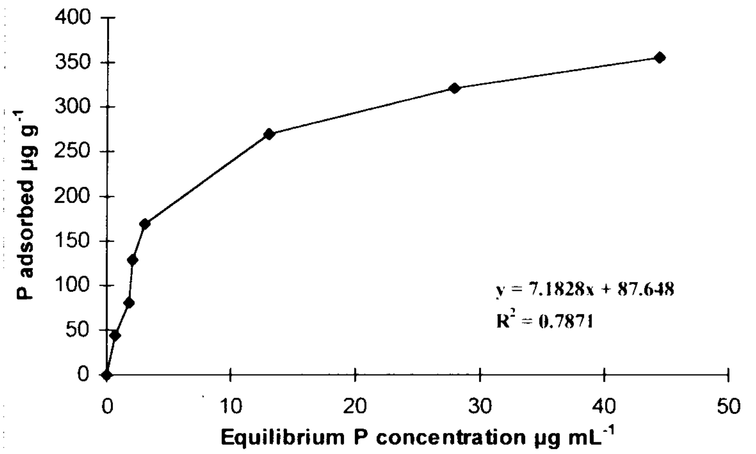

Fig. 1. Phosphorus Adsorption isotherm

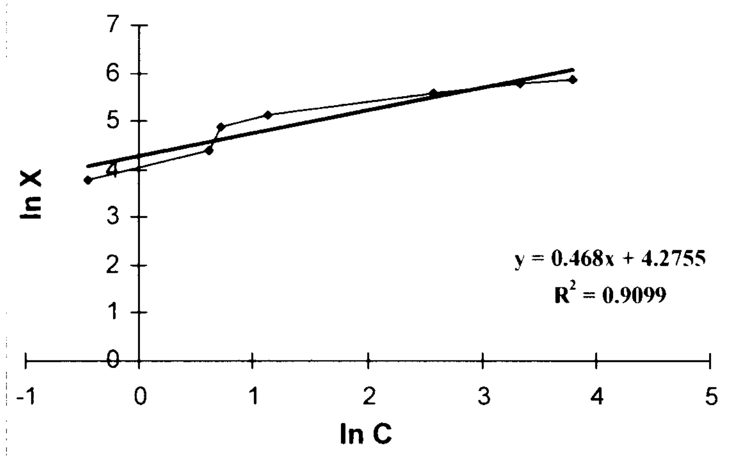

Fig. 2. Fitted modified Freundlich equation on P sorption data

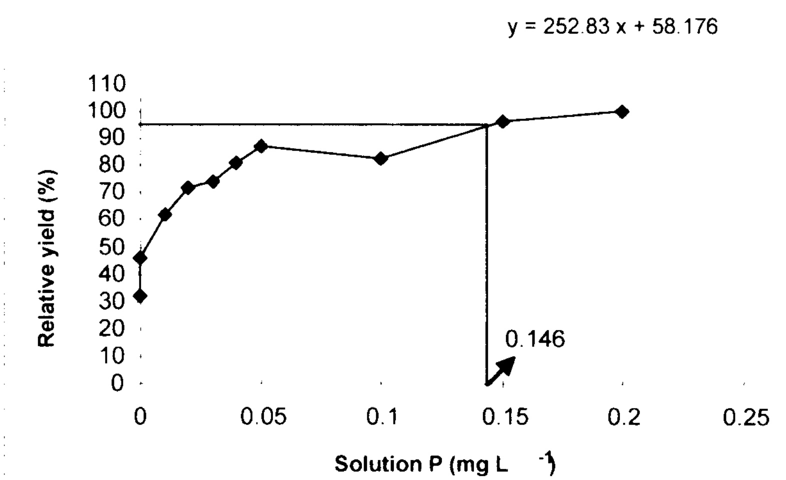

Fig. 3. External phosphorus requirement of wheat

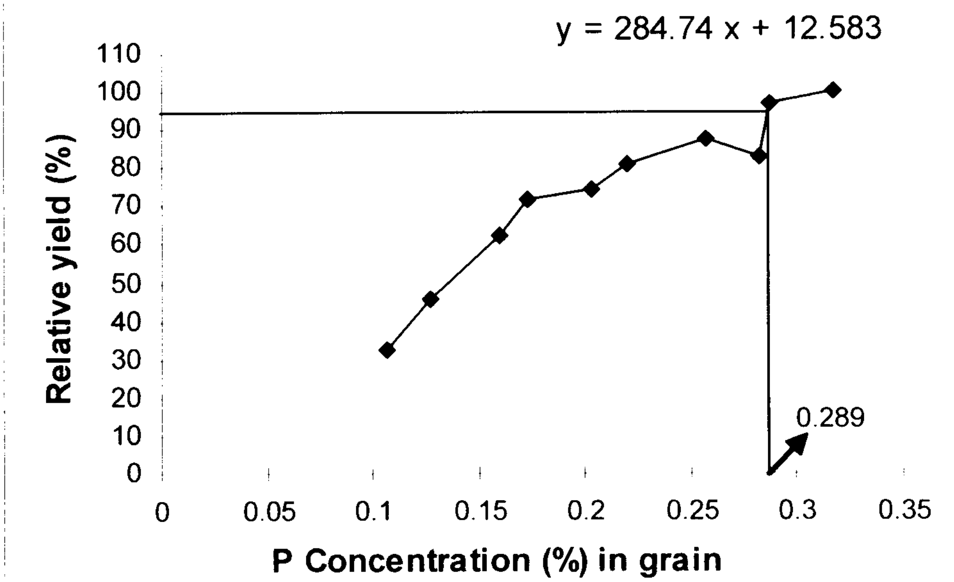

Fig. 4. Internal phosphorus requirement of wheat

requirements are crop specific and site specific and can be estimated as external and internal P requirements. Fox (1981) reported that P requirement, both external and internal, of most crops were greater during early stages of growth than for crops approaching to maturity.

External (solution) P requirement of wheat

The solution levels developed for wheat growth were plotted against 95 % relative yield of wheat for the determination of P requirement by the Boundary Line Technique (Webb, 1972) as shown in the Fig. 3. The graph revealed that solution P requirement of 0.146 mg L^{-1} was found in Rasulpur soil series for near maximum yield of wheat (95 %). This value elucidated that near maximum yield of wheat (95 %) was obtained at lower solution P level. This means that P requirement is very low in coarse textured soil with respect to yield and the reason might be that coarse textured soil has a low P fixation capacity. Memon *et al.* (1991) found that 18-29 kg P ha^{-1} is required to develop a solution level of 0.032 mg P L^{-1} in calcareous soils. The concentration at the root surface of young plants need about 0.03-0.3 mg P L^{-1} and older plants require about 0.03 mg P L^{-1} or less. The concentrations which is required in bulk soil solution are little higher (0.06-0.68 mg P L^{-1}) and this would be expected because uptake reduces the phosphate concentration at the root surface when plants are grown in static systems e.g. soils (Kamprath and Watson, 1980). Similarly, Beckwith (1965) suggested a standard concentration of 0.2 ug P mL^{-1} as adequate for most plant species. Similar results were found by Nisar (1988), Memon *et al.* (1991) and Hassan *et al.* (1993 & 1994) under soil conditions in Pakistan.

Internal P requirement of wheat

Internal P requirement of wheat was determined at crop maturity i.e. in grain by making a graph of P concentration in grain and maximum attainable 95 % relative yield as shown in Fig. 4. The value obtained for internal P requirement of wheat was 0.289 % (Fig. 4). This means that as the crop passed through reproductive phase, the P was translocated to the seed and this transfer of P was very rapid and highest in this coarse textured soil. Critical P concentration in wheat grains for near maximum grain yield normally ranges from 0.19 % to 0.25 %. Rashid (1992) found critical P concentration in wheat grain as 0.22 % and in maize grain as 0.27 % under green house conditions.

It can be concluded from this study that application of adsorption isotherm in Freundlich model was quite effective in determining the phosphorus requirement of wheat. Maximum grain and straw yields of 3.37 and 3.50 Mg ha^{-1} was recorded at solution P level of 0.20 mg P L^{-1}, respectively. Phosphorus concentration in grain and straw was 0.410 and 0.138 % which was found at solution P level of 0.40 mg P L^{-1}, respectively. External solution P requirement was 0.146 mg P L^{-1} and internal P requirement was found 0.289 % for obtaining 95 % relative yield of wheat. Further research is still needed on this aspect to formulate some concrete fertilizer recommendation by using the model approach.

REFERENCES

Ahmad, N., M. Abid, K. Hussain, M. Akram and M. Yousaf. 2003. Evaluation of nutrient status in rice growing areas of the Punjab. Asian J. Plant Sci. 2(5): 449-453.

Amrani, M., D.G. Westfall and L. Mustafa. 1999. Improving the soil test phosphorus calibration for calcareous soils. Commun. Soil Sci. Plant Anal. 30(1-2): 129-144.

Arshed, M., Rahmatullah, M. Salim and M. Yousaf. 2000. Soil properties related to phosphorus sorption as described by modified Freundlich equation in some soils. Int. J. Agri. Biol. 2: 290-292.

Aslam, M., M.S. Zia, Rahmatullah and M. Yasin. 2000. Application of Freundlich adsorption isotherm to determine phosphorus requirement of several rice soils. Int. J. Agri. Biol. 2: 286-288.

Beckwith, R.S. 1965. Sorbed phosphate at standard supernatant concentration as an estimate of the phosphate needs of soils. Aust. J. Exp. Agri. and Anl. Hus. 5: 52-58.

Chaudhry, E.H., A.M. Ranjha, M.A. Gill and S.M. Mehdi. 2003. Phosphorus requirement of maize in relation to soil characteristics. Int. J. Agric. Bio. 5(4): 625-629.

Duivenbooden, N.Van, C.T. deWit and H. vanKeulen. 1996. Nitrogen, Phosphorus and Potassium relation in five major cereals reviewed in respect to fertilizer recommendations using simulation modeling. Fert. Res. 44: 37-49.

Fitter, A.H. and C.D. Sutton. 1975. The use of the Freundlich isotherm for soil P sorption data. J. Soil Sci. 26: 241- 246.

Fox, R.L. 1981. External Phosphorus requirement of crops. In M. Shelly *et al.* (Ed). Chemistry in the soil environment. Am. Soc. of Agron. Madison, WI, USA. p. 223-239.

Fox, R.L., R.P. Bossbart, D. Somponge and M.L. Lin. 1989. Phosphorus requirements and management of sugarcane, pineapple and bananas. In. Proc. "P requirements for Suitable Agriculture in Asia and Ocean". March 5-10. Los Banos, Philippines.

Hassan, M.M., A. Rashid and M.S. Akhtar. 1993. Phosphorus requirement of corn and sunflower grown oncalcareous soils of Pakistan. Commun. Soil Sci. Plant Anal. 24: 1529-1541.

Hassan, M.M., A. Rashid and M.S. Akhtar. 1994. Phosphorus requirement of maize and sunflower on selected bench mark soils of Pakistan. In Proc. 4th Nat. Cong. Soil Sci. May 24-26, 1992 at NARC, Islamabad. p. 327-332.

Holford, I. 1989. Phosphorous behavior in soils. Agri. Sci.12: 15- 20.

Javid, S. and D.L. Rowell. 2003. Effect of soil properties on Phosphate adsorption in calcareous soils of Pakistan. Pak. J. Soil Sci. 21(4): 47-55.

Juo, A.S.R. and R.L. Fox. 1977. Phosphate sorption capacity of some benchmark soils in West Africa. Soil Sci. 143: 370-376.

Kamprath, E.J. and M.E. Watson. 1980. Conventional soil and tissue test for assessing the phosphorus status of soils. In F.E. Khawsaneh *et al.* (Ed) "The role of Phosphorus in Agriculture". Soil Sci. Soc. Am. Madison, WI., USA. p. 433-469.

Khattak, J.K. and J. Iqbal. 1992. Calibration of phosphorus on calcareous soils by $NaHCO_3$ and NH_4HCO_3- DTPA extracting using maize as a test crop. In proc. "Role of Phosphorus in Crop Production." NFDC, Islamabad, Pakistan. p. 311-320.

Kuo, S. and E.G. Lotse. 1974. Kinetics of phosphate adsorption and desorption by lake sediments. Soil Sci. Soc. Am. Proc. 38: 50-54.

Le Mare, P.H. 1982. Sorption of isotopically exchangeable and non-exchangeable phosphate by some soils of Colombia and Brazil, and comparisons with soils of southern Nigeria. J. Soil Sci. 33: 691-707.

Memon, K.S., A. Rashid and H.K. Puno. 1992. Phosphorus deficiency diagnosis and P soil test calibration in Pakistan. Tropical Soil Bulletin No. 92-02, Phosphorus Decision Support System Workshop, March 11-12, 1992. College Station, Texas, University of Hawaii, Honolulu, USA.

Memon, K.S., H.K. Puno and R.L. Fox. 1991. Phosphate sorption approach for determining phosphorus requirements of wheat in calcareous soils. Fert. Res. 28(1): 67- 72.

Moodie, C.D., H.W. Smith and R.A. Mcreery. 1959. Laboratory manual for soil fertility. State college of Washington, Mimeograph, Pullman Washington, D. C. USA. p. 31-39.

Murphy, J. and H.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27: 31-36.

Nair, P.S., T.J. Logan, A.N. Sharpley, L.E. Somers, M.A. Tabatabai and T.L. Yuan. 1994. Inter laboratory Comparison of a Standardized Phosphorus Adsorption Procedure. J. Environ. Qual. 13(4): 591-595.

NFDC. 2003. Fertilizers and their use in Pakistan. 3rd edition (Ahmad, N. and M. Rashid ed). National Fertilizer Development Centre, Islamabad. p. 76.

Nisar, A. 1988. Phosphorus use efficiency and soil test crop response correlation. Ph. D. Thesis. Dept. Soil Sci., Uni. Agri., Faisalabad, Pakistan.

Patel, N.M., R.P.S. Ahlawat and R.B. Ardeshna. 1997. Direct and residual effect of Phosphorus in rice-wheat sequence under south Gujrat conditions. Ind. J. Agron. 42(1): 18-21.

Probert, M.E. 1983. The sorption of phosphates by soil. In: "Soils: an Australian viewpoint." Division of Soils, CSIRO, Melbourne, Australia. p. 429-435.

Rashid, A. 1992. Internal P requirement of crops and use of universal soil test for evaluating P fertility of Pakistani soils. In Proc. "Role of Phosphorus in Crop Production." July 15-17, 1990. NFDC, Islamabad, Pakistan. p. 147-173.

Rathowsky, D.S. 1986. A statistical study of seven curves for describing the sorption of phosphate by soil. J. Soil Sci. 37: 183- 189.

Rowell, D.L. 1994. Soil Science. Methods and Applications. Longman Scientific and Technical, Harlow, Essex, UK.

Saeed, M., Z.A. Ahmad and M.Y. Nadeem. 1992. Residual effect of Phosphorus applied to rice on wheat and vice versa. In Proc. "Role of Phosphorus in Crop Production." July 15-17, 1990. NFDC, Islamabad, Pakistan. p. 415-423.

Sharma, R.D. and T.A. Singh. 1998. Direct and residual affect of liquid ammonium poly phosphate as a phosphorus source in wheat (Triticum aestivum) – maize (Zea mays) cropping systems in an Entisol of western Utter pardesh. Ind. J. Agron. 43(2): 223-230.

Steel, R.G.D. and J.H. Torrie. 1980. Principles and Procedures of Statistics. 2nd Ed. Mc Graw-Hill Book Corp. Inc., NY, USA.

Tomar, N.K. and R.S. Pundir. 1999. Effect of exchangeable sodium percentage on the efficiency of diammonium orthophosphate and ammonium polyphosphate in wheat. J. Indian Soc. Soil Sci. 45: 107-112.

U.S. Salinity Lab. Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. USDA Handbook No. 60, Washington, DC, USA.

Vander zaag, P., R. Fox, R.S. Delapena, W.M. Laughlin, A. Ryskamp, S. Villa-gracia and D.T. Westermann. 1979. The utility of phosphate sorption curves for transferring soil management information. Trop. Agri. 56: 153-160.

Watanabe, F.S. and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Am. proc. 29: 677-678.

Webb, R.A. 1972. Use of boundary line technique in the analysis of biology data. J. Hort. Sci. 47: 309-319.

White, R.E. 1982. Retention and release of phosphate by soil and soil constituents. In: Soils in Agriculture, Critical reports on applied Chemistry. Vol. 2. Soc. Chem. Tinker, P. E. (ed). p. 71-114. Industry, Blackwell Scientific Publications, Oxford, UK.