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Adsorption Capacities and Availability of Phosphorus in Soil Solution for Rice Wheat Cropping System

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Abstract: The present study was conducted to measure the phosphorus (P) adsorption capacities in a typic Camborthid (Bhalike series) soil of rice tract of Punjab, Pakistan to compute P fertilizer quantities for field application, internal and external P requirements of the wheat, sorghum fodder and rice, Phosphorus Fertility Build-up Factor (PFBF) and level of phosphorus build-up. The soil selection was based on clay percentage, calcium carbonate content. The data showed that soil was free from salinity and sodicity, deficient in organic matter and adequate in available potassium. Sorption isotherm was constructed in the laboratory by equilibrating and shaking 2.5 g soil with 25 ml of 10 m M $CaCl_2$ containing 0, 5, 10, 15, 20, 40, 60 and 80 g P mL^{-1} as KH_2PO_4 for 24 h. Sorption data was fitted into linear form of Langmuir and modified Freundlich models and P adsorption capacity was determined from the equations. Theoretical doses were computed from modified Freundlich model for field application. The studies were conducted in permanent layout according to Randomized Complete Block Design (RCBD) with three replications. Different theoretical P doses were applied in the field to develop soil solution P level of 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} alongwith a control of native P soil solution. An overall check (NK = 0 with native P) was also kept. Recommended doses of N and K were applied to all the crops alongwith recommended agronomic practices. Phosphorus was also applied @ 13.65 and 19.65 mg P kg^{-1} to subsequent sorghum fodder and rice crops, respectively. Plant sampling was done at booting stage of wheat and rice and at the harvest of each crop. Maximum P adsorption was found 555-µg g^{-1} with buffering capacity of 116.55-µg g^{-1} soil. Maximum wheat grain yield was 4.24 Mg ha^{-1}; sorghum fresh fodder yield was 48.95 Mg ha^{-1} and rice paddy yield was 4.38 Mg ha^{-1}. Total P uptake by wheat was 19.91 kg ha^{-1}, by sorghum fodder it was 34.67 kg ha^{-1} and by rice P uptake of 20.49 kg ha^{-1} was measured. Mean phosphorus fertility build-up factor (mg P required to build 1 mg P kg^{-1} soil) was 18.51 and the level of P buildup (mg P kg^{-1} built-up in soil for each mg P kg^{-1} soil applied) was 0.054. Level of P depletion was 0.154 mg P kg^{-1} for NPK check plots while 0.173 mg P kg^{-1} for P check plots. Internal P requirement (for 95% relative yield) for wheat was 0.249% at booting stage and 0.277% for grain stage. For sorghum fodder, internal P requirement was 0.326% and for rice, it was 0.165% at booting stage and 0.220% for paddy stage. So plant sampling at booting stage best correlated the results with 95% relative yield of rice and wheat. External Olsen P requirement for wheat was 13.80 mg kg^{-1}, for sorghum fodder 12.68 mg kg^{-1} and for rice, 10.05 mg kg^{-1}, respectively. External solution P requirement for wheat was 0.252 mg L^{-1}.

Key words: Phosphorus · langmuir and modified freundlich model · wheat · sorghum fodder · rice · internal and external P requirement · PFBF

INTRODUCTION

Agriculturally productive soils of Pakistan are alluvial. These soils are important because they occupy significant proportion of earth's surface and support high population densities such as Indo-Gigantic plains. These soils in the rice tract of Pakistan are deficient in available phosphorus (P) and the native P supply cannot cope with P mining due to continuous cropping. According to Malik *et al.* [1] and NFDC [2], 93% of the soils of Pakistan contain less than 10 mg kg^{-1} Olsen extractable P and are thus deficient. Mineral fertilizers have played a major role towards improving crop yields but major constraint in achieving proven crop potential is imbalanced use of

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fertilizers, particularly low P use as compared to N. Thus, P fertilization is essential.

Soils of Pakistan are alkaline (pH>7.0) and mostly calcareous ($CaCO_3$>3.0%) in nature. When phosphatic fertilizers are added, part of them go to soil solution and is taken up by plants, while rest goes to exchange sites and is either adsorbed or precipitated and is a serious problem [3]. Soil texture, especially clay content, influences the phosphorus supplying power of a soil [4]. The extent of P sorption is relatively higher in fertilized soil and progressively decreases with increasing rate of fertilizer P in both manured and unmanured soils [5]. Relatively few studies, particularly in calcareous soils, have been directed towards the relationship between chemical properties and P adsorption and desorption characteristics of the soils. It was therefore, considered worth while to study the phosphate adsorption and its release in calcareous soils of different origin and properties to categorize them, if possible, for their capacities for P adsorption and release. This could help to predict the fertilizer requirement of such soils as accurately as possible for economic crop production.

Fox and Kamprath [6] constructed phosphate sorption isotherms to describe the relationship between levels of P in solution established after fertilization in laboratory and the quantities of P sorbed at the end of equilibrium. This approach has an advantage over conventional method of soil testing in that it integrates P intensity, capacity and quantity aspect of the soil, all of 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. Soil solution P is an immediate source for plant P uptake [7] and standard solution P concentration (0.2 mg L^{-1}) provides adequate P for many crops if it is continuously maintained in the medium [8]. Many equations e.g. Langmuir, modified Freundlich, Gunary, Tempkin and mechanistic models have been used to describe P adsorption in most recent work and have successfully confirmed phosphate adsorption relationships [9]. The Langmuir and the Freundlich equations described the adsorption phenomena satisfactorily [10]. Ghanbari *et al*. [11] fitted the Langmuir and the Freundlich isotherms to P adsorption data for 10 calcareous soils and observed that adsorption data closely followed the Freundlich isotherm while the Langmuir isotherm was positively correlated with pH, clay and CEC and negatively correlated with $CaCO_3$ in a multiple regression analysis. Linear relationship was observed between P adsorption and desorption. The slope of line was different for different soils [12].

The nutrient requirement of a crop can be expressed in several modes and channels. 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" [13]. 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. Beckwith [8] suggested a standard concentration of 0.2 mg P L^{-1} because it is an adequate concentration of P in solution for most plant species. However, Beckwith did not propose 0.2 mg P L^{-1} as a universal P requirement for all crops. On the other hand, Fox [14] stated that the most crops require less P than 0.2 mg P L^{-1} in solution. Fox [13] demonstrated that the external P requirement is not a single valued constant that holds for all conditions. He 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. Critical level is the soil test P below which the yield response to applied P is more probable and the amount of P required to raise soil test level by 1 mg kg^{-1} (buffered capacity) depends upon local conditions and management practices.

A large number of studies on many plant species have shown that early season phosphorus supply is critical for optimum crop yield and P restrictions during the first four to six weeks of growth lead to large reductions in tillering and head formation in wheat [15-17]. When the supply of the plant available P in the soil is high, the soil may supply sufficient P to the plant to optimize economic crop yield [18].

Residual effect of P by the criteria of crop yield and soil analysis for P content showed a significant increase in the yield of subsequent wheat crop without P fertilizer application in the rice-wheat rotation [19, 20]. Puno [21] studied the phosphorus fertility build-up factor (PFBF) and Olsen P content in relation to P fertilization up to 32.8 mg kg^{-1} (150 kg P_2O_5 ha^{-1}) in silt loam soil and found that PFBF ranged from 11.8-49.3 mg kg^{-1}. Firat and Gumus [22] observed the residual effect and continuous application of P fertilizer in an alluvial soil increased the amount of available P in the soil solution and P concentration in plants. So keeping in view all the facts, a study was planned in alluvial soils of rice tract with the following objectives:

(1) Construction of P adsorption isotherms and fitting data to Langmuir and modified Freundlich equations for computing P fertilizer doses to raise soil solution P level for maximum yield.
(2) To determine the internal and external phosphorus requirement of wheat, sorghum (fodder) and rice.
(3) To see the level of P build-up and depletion following wheat-sorghum (fodder)-rice rotation.

MATERIALS AND METHODS

These investigations were carried out in typic Camborthid (Bhalike series) soil of the rice-growing tract of the Punjab, Pakistan. Soil was selected on the basis of calcareousness and clay contents and a composite soil sample was collected from 0-20 cm depth, air-dried, sieved through a 2 mm sieve and stored for analyses. All basic analyses were performed for chemical characteristics of the soils based on methods described in Methods of Soil Analysis [23, 24] except texture by Moodie *et al*. [25], available phosphorus by Watanabe and Olsen [26] and Murphy and Riley [27] and Organic matter by Walkley and Black [28].

Laboratory study

Construction of phosphorus adsorption isotherm and model application: Adsorption isotherms are used to measure the phosphate adsorption capacities of the soils, to evaluate the residual effect of phosphatic fertilizers and to estimate P requirements of soils and crops [6, 29-31]. To a 2.5 g sample of soil, 25 ml of 10 mM $CaCl_2$ solution containing a series of phosphate concentrations was added as described by Rowell [32]. The initial concentration of P in solution ranged from 0-80 (0, 5, 10, 15, 20, 40, 60 and 80) µg P mL^{-1}, with close intervals between the low concentrations. The samples were shaken on end over end shaker for 24 h and were filtered through a Whatman no. 42 filter paper. The phosphate concentration in the final solution was determined. The difference between amount of P in solution before and after equilibrium was taken as the amount of P sorbed [33]. The sorption isotherms were examined by the simple Langmuir and modified Freundlich equations as proposed by Le Mare [34].

Langmuir model: The Langmuir equation was first used to describe phosphate adsorption by Olsen and Watanabe [35] and has since been used. The main advantage of this equation is that it allows P adsorption maxima of soils and the binding energy for P sorption to be calculated [36, 37]. It does not give a straight line when c/x is plotted against c for a wide range of P concentration [38]. The Langmuir equation [39] correlated the amount of P adsorbed with the equilibrium aqueous P concentrations. The common form of the Langmuir equation may be written as:

$$X= k\, b\, C/1 + C \quad (1)$$

Where
X = Amount of P (µg) sorbed per g soil
C = Equilibrium solution concentration of P (mg L^{-1})
k = Affinity coefficient between phosphate ions and the surface of soil particles (L mg^{-1} P) i.e. constant related to bonding energy of soil for P.
b = Maximum amount of adsorbate that can be adsorbed i.e. a complete monomolecular layer mg P kg^{-1} soil.

In a linear form, the equation [1] can be written as:

$$C/X = 1/kb + C/b \quad (2)$$

The parameters of equation [2] i.e. 1/k and b were calculated using linear regression equations fitted to the original data. The 1/k was constant and b was inverse of slope of the regression equations. If adsorption data conform to the Langmuir equation, plots of C/X vs C yields a straight line with a slope 1/b and intercept 1/kb.

Modified freundlich model: The sorption isotherms were also examined using the modified Freundlich model. The Freundlich model is the oldest adsorption model in the literature on soil phosphate, first used by Russell and Prescott [40]. It is an empirical model and corresponds to a model of adsorption in which the affinity term decreases exponentially as the amount of adsorption increases. Over a limited range of concentration, the Freundlich model often describes adsorption well [41]. The simple form of the Freundlich model was proposed by Le Mare [34] as follows:

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

Where 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 at which this point occurs varies between soils. The modified Freundlich model used to describe the soils in this work is as follows:

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

The main advantage of this equation is that a and b are the amount 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 of P and phosphatic fertilizers required to develop P levels in soil solutions under field conditions were calculated from this equation.

Field studies

Phosphorus build-up in soil: The objective of this study was to monitor the rate of P build up and Phosphorus Fertility Buildup Factor (PFBF) in soil by using cereal based multiple cropping system and internal and external P requirement of crops. The experiment was conducted in permanent lay out which included three crops i.e. wheat (November to April), sorghum fodder (May to June) and rice (July to October) with fourteen treatments arranged in randomized complete block design (RCBD) with three replications having plot size of 6x 4 m. All the agronomic and recommended cultural practices were followed for normal growth of the crops. Wheat crop cv. Inqalab-91 was sown with seed rate of 125 kg ha^{-1} during the second week of November after treating the seed with benlate @ 100 g per 40 kg. Half of the recommended nitrogen (70 kg ha^{-1}) and potassium (K_2O) @ 70 kg ha^{-1} along with phosphorus (P_2O_5) doses (Table 6) calculated from modified Freundlich model for developing soil solution P levels were applied at sowing time in the form of urea, potassium sulphate and single super phosphate, respectively by broadcast method. Second half of nitrogen was applied at first irrigation. Plant sampling (20-25 above ground portion of plants) at booting stage was done to observe the P concentration [42].

The crop was harvested at maturity. Grain and biomass yields were recorded by harvesting the whole experimental unit (6x4 m). The grain and straw samples were analysed to calculate the P uptake by the crop using the formula

$$\text{Total P uptake (kg ha}^{-1}\text{)} = \text{Grain P uptake} + \text{Straw P uptake}$$

$$\text{P uptake (kg ha}^{-1}\text{)} = \text{P Concentration (\%)} \times \text{yield (Mg ha}^{-1}\text{)} \times 1000/100$$

Post harvest soil sampling was also done immediately after harvest of wheat crop for the determination of Olsen P. After wheat harvest, sorghum cv. Hegari was raised to reap the benefits as animal fodder at seed rate of 75 kg ha^{-1} with recommended dose of N (62.5 kg ha^{-1}) and P_2O_5 (62.5 kg ha^{-1}). Fodder was harvested after 55 days of growth and fresh fodder yield was recorded. Plant samples were collected and oven dried at 70°C for analysis to measure oven-dried weight of fodder and P uptake. Post harvest soil samples were also collected for Olsen P analysis. After sorghum fodder, fine rice cv. Super Basmati was transplanted in the second week of July. Half of recommended N (55 kg ha^{-1}), all P_2O_5 (90 kg ha^{-1}) and K_2O (70 kg ha^{-1}) were applied as basal dose and remaining half N with $ZnSO_4$ @ 12.5 kg ha^{-1} were applied after 30 days of transplanting. Plant sampling at booting stage was done from 25 above ground portion of rice plants. At maturity, paddy and straw yields were recorded and their respective samples were collected, oven dried and analysed for P contents. Soil samples were also taken at harvest for Olsen P determinations.

Relative 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 and was calculated by the formula

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

Where,

Threshold yield	=	Yield at zero level of x
Plateau yield	=	Point of maximum response to x
x	=	Rate of nutrient (P) applied.

Phosphorus fertility build-up factor (PFBF): PFBF was calculated by the total amount of P added (mg kg^{-1} soil) divided by Olsen-extractable P (mg kg^{-1} soil) after the last crop.

Level of phosphorus build-up: It was calculated by the net increase in Olsen P (mg kg^{-1} soil) after the third crop divided by the total P added (mg kg^{-1} soil).

Internal phosphorus requirement of crops: Internal P requirement of each crop was determined from the regression equation by plotting the relative yield (95%) against the P concentration (%) in the respective plant part.

External phosphorus requirement of crops: External Olsen and solution P requirement of crop was determined from the regression equation by plotting the graph between 95% relative yield and the Olsen P or solution P level after the harvest of each crop.

Statistical analysis: Analysis of variance (ANOVA) technique was used and Duncan's multiple range test (DMR) was applied to see the significance of difference among treatment means [43]. Regression and correlation was applied to compute build-up and depletion in soil P status in alluvial soils used in these investigations by the procedures as described by Steel and Torrie [44].

RESULTS AND DISCUSSION

The physical and chemical characteristics of the soil used in this study are given in Table 1. The soil was clay loam in texture having clay content 33% and was non-saline and non-sodic. Calcium carbonate content was 7.82% indicating that soil was moderately calcareous in nature and was deficient in organic matter and available phosphorus but medium in extractable Potassium.

Construction of langmuir and modified freundlich isotherms: Sorption isotherm was constructed by shaking 2.5 g soil with 25 mL of 10 mM $CaCl_2$ solution containing different P concentrations ranging from 0 to 80 µg mL^{-1}, for 24 h.

The adsorption curve presented in Fig. 1 revealed that isotherm showed maximum P was fixed at low P concentrations. The soil was calcareous and low in organic matter content and thus did not show any precipitation upto the P application level of 80 µg mL^{-1}.

Langmuir plots of the sorption data: The Langmuir equation was first used to describe phosphate adsorption by Olsen and Watanabe [35] and has since been widely used.

Table 1: Original soil analysis of the selected soil series.

Determinant	Units	Values
Sand	%	39
Silt	%	28
Clay	%	33
Textural class	-	Clay loam
Sub group	-	Typic camborthid
PHs	-	8.20
ECe	dSm^{-1}	1.22
SAR	$(mmol\ L^{-1})^{0.5}$	1.02
$CaCO_3$	%	7.82
Organic matter	%	0.76
Olsen P	mg kg^{-1}	5.20
Extractable K	mg kg^{-1}	145

Table 2: Phosphorus sorption parameters of the Langmuir model.

Maximum adsorption (b) µg g^{-1}	Affinity coefficient (k) mL g^{-1}	Maximum buffering capacity (bk) µg g^{-1}	Correlation coefficient (r^2)
555	0.21	116.55	0.99

Table 3: Phosphorus sorption parameters of the freundlich model

Amount adsorbed (a) µg g^{-1}	Buffer capacity (b) mL g^{-1}	Correlation coefficient (r^2)	No. of values (n)
98.61	50.76	0.94	8

Table 2 and Fig. 2 present the Langmuir parameters i.e. maximum adsorption (b), affinity coefficient (k), maximum buffering capacity (bk) and correlation coefficient (r^2) computed from the linear regression when phosphorus was applied @ 0 to 80 µg P mL^{-1} and equilibrated the soil for 24 h. The maximum adsorption (b) could be used to estimate the amount of phosphatic fertilizer to be added to an unfertilized soil. The affinity coefficient (k) indicates comparatively how easily the added phosphorus is adsorbed on or released from the adsorbing surface. The affinity coefficient sequence followed that of bk's. Various soil properties like P concentration, amount of clay, $CaCO_3$, etc. have been reported to contribute to P fixation in soils [3, 30, 31]. Looking at the r2 value assessed the goodness of the fit of the model. Many research workers have successfully conformed P adsorption relationships using different equations [10, 12]. The plot was highly linearly correlated with r^2>0.95 indicating apparent high conformity of the adsorption data to the Langmuir model. From the plots (C/X vs C), maximum adsorption (b) and bonding energy (k) were calculated for the soil when incubated for 24 h.

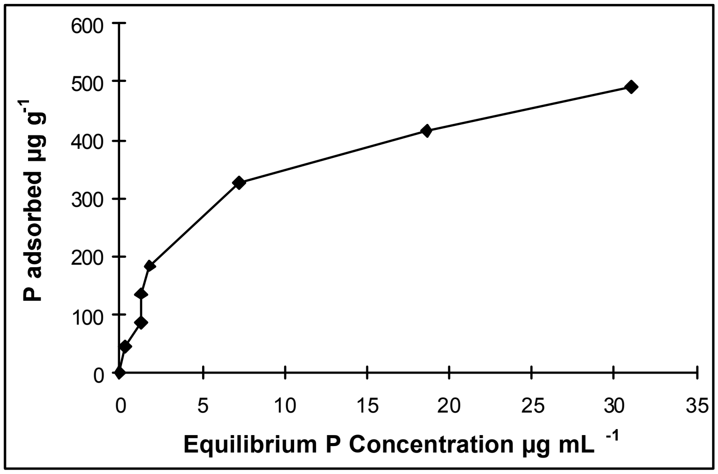


Fig. 1: Phosphorus sorption isotherm of the soil

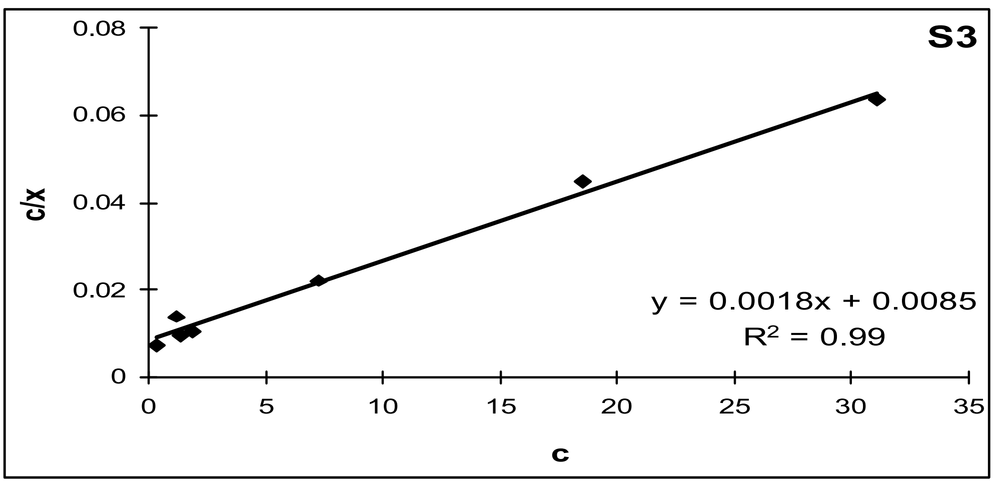


Fig. 2: Fitted Langmuir equation on P sorption data

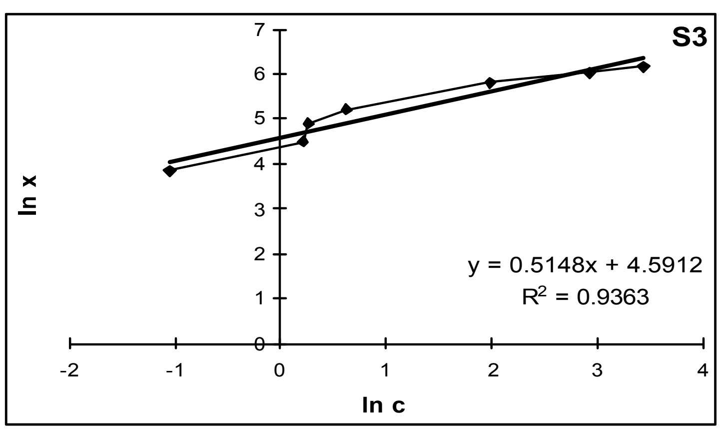


Fig. 3: Fitted modified Freundlich equation on P sorption data

From these two parameters i.e. maximum adsorption (b) and bonding energy (k), maximum buffering capacity (bk) was computed. The maximum adsorption (b), P adsorption energy (k) and maximum buffering capacity (bk) were 555 µg g^{-1}, 0.210 mL g^{-1} and 116.55 µg g^{-1}, respectively. The mean correlation (r^2 = 0.99) for the plots was significant and positive for all soils. Balluax and Peaslee [45] explained that there was an exponential inverse relationship between b and k parameters for soils. Muljadi *et al*. [46] found wide difference between k values for P adsorption and its possibility due to distinct mechanism, involving different components in sorption P.

The maximum buffering capacity (bk) which is a capacity factor, measures the ability of the soil to replenish phosphate ions to soil solution as they tend to be depleted. The fact that Langmuir model is only valid within low equilibrium concentration ranges and bk a useful tool in describing a property of soil with high adsorption capacity [7].

Dominant minerals present in the clay size fractions of Pakistan soils are mica, kaolonite, chlorite, smectite and vermiculite [47, 48]. So these soils have a mixed mineralogy. Many research workers have found that when similar kinds of minerals are present, then amount of clay is important for P sorption [6, 49, 50].

Freundlich plot of sorption data: The sorption isotherm of modified Freundlich equation was also examined. The linear plot of the modified Freundlich equation for the soil is presented in Fig. 3 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 amount adsorbed (a) was 98.61 µg g^{-1} and the buffering capacity (b) of the soil was 50.76. The goodness of the fit of the model was ascertained by looking at the r^2 value (0.94) indicating high conformity of the adsorption data with the Freundlich model. The values of the Freundlich b parameter followed the same order as the Langmuir b parameters as given in Table 4. The linearization transformation of data showed that the plot was linear. Generally the Freundlich model seemed fit at medium and high equilibrium concentrations. The value of the exponent was found<1 (Table 5) that relates to the characteristics of the adsorbent (soil or $CaCO_3$). The findings are in agreement with those of Kuo and Lotse [51] 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 meaningless. 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 isotherm would be a straight line. Using the P adsorption parameters, the Freundlich plot equation for the soil was formulated (Table 5) on the basis of these values which was computed as P = 98.61 $C^{0.515}$. Although the Freundlich equation is empirical yet it implies that sorption decreased exponentially with increasing saturation of exchange sites. This scenario seems close to the reality than assumption of constant bonding energy inherent in Langmuir plot. Fitter and Sutton [52, 53] reported similar observations.

Table 4. Comparison of b values of models

Freundlich b	Langmuir b
50.76	555

Table 5: Comparison of langmuir and modified freundlich models

Langmuir equation		Modified freundlich equation	
Model form	Linear form	Model form	Linear form
X=(bkC)/1+(k)(C)		P= $aC^{b/a}$	
X=(555)(0.210)C/1 +(0.210)C	Y=0.0018x+0.0085	P=98.61 $C^{0.515}$	Y=0.5148x+4.5912

Computed P doses to be applied for different soil series: The Langmuir and Freundlich models could be used over the equilibrium concentrations within which each model is valid. 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 soils over wide range of equilibrium concentrations. The Langmuir has its merits at low P concentration and it is justifiable to use Langmuir parameter bk for characterizing soil only at low P intensities. Since the soils under this study were prone to high P fixation, therefore, linear form of modified Freundlich model 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.,

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

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

Table 6: Computed P doses to be applied in the field

Treatments	P in soil solution (mg L^{-1})	P (mg kg^{-1} soil) to be added	P_2O_5 (kg ha^{-1}) to be added
T1	Native (0 NK)	0	0
T2	Native (+ NK)	0	0
T3	0.01	9.20	42.14
T4	0.02	13.15	60.23
T5	0.03	16.20	74.20
T6	0.04	18.79	86.06
T7	0.05	21.08	96.55
T8	0.10	30.12	137.95
T9	0.15	37.12	170.01
T10	0.20	43.05	197.17
T11	0.25	48.29	221.16
T12	0.30	53.04	242.92
T13	0.40	61.51	281.75
T14	0.50	69.00	316.02

Table 7: Yields of wheat, sorghum and rice crops (Mg ha^{-1})

	Wheat		Sorghum fodder		Rice	
Treatments	Grain	Straw	Fresh	Oven dried	Paddy	Straw
T1	1.07K	1.19K	18.09M	3.96M	1.73J	1.86M
T2	1.24J	1.37J	18.92M	4.14M	1.88I	2.01L
T3	2.25I	2.37I	21.08L	4.62L	2.48H	2.39K
T4	2.59H	2.72H	22.92K	5.02K	2.77G	2.60J
T5	2.91G	3.04G	26.26J	5.75J	3.12F	2.85I
T6	2.35F	3.47F	28.79I	6.30I	3.44E	3.19H
T7	3.56E	3.67E	30.67H	6.72H	3.67D	3.60G
T8	3.72D	3.85D	33.63G	7.36G	3.83C	3.68FG
T9	3.81CD	3.95CD	35.79F	7.84F	4.14B	3.79F
T10	3.87C	4.01C	38.17E	8.36E	4.38A	3.97E
T11	4.15B	4.27B	40.88D	8.95D	4.46A	4.23D
T12	4.24AB	4.36AB	43.96C	9.63C	4.45A	4.43C
T13	4.30A	4.42A	46.16B	10.11B	4.44A	4.84B
T14	4.25AB	4.39AB	48.95A	10.72A	4.45A	5.08A
LSD	0.1303	0.1295	0.9023	0.1986	0.1401	0.1307

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

The P quantities computed as mg P kg^{-1} soil and kg P_2O_5 ha^{-1} (Table 6) were applied to the field for further studies. Field studies were conducted to monitor the rate of phosphorus build-up by following the wheat-sorghum fodder-rice crop rotation. Computed P quantities (Table 6) from Modified Freundlich model were applied to wheat crop to develop solution P levels from 0.01 to 0.50 mg L^{-1}. The results are described as under.

CROP yields (Mg ha^{-1})

Wheat grain and straw yield: Wheat gain and straw yield is data given in Table 7, which indicated that both grain and straw yield increased with an increase in solution P levels. The maximum grain and straw yield was obtained at solution concentration of 0.30 mg P L^{-1}, which was developed by adding 242.92 kg P_2O_5 ha^{-1}. The yields were significantly increased at lower level of solution and the yield was at par at 0.30 and 0.25 mg P L^{-1}. The yields at native solution P level where only NK was applied were significantly higher than where no NK was applied. The results are in line with those of Memon [54] who described a solution level of 0.009 mg P L^{-1} for 75% of maximum yield of wheat and 0.028 mg P L^{-1} for 95% of maximum yield. According to FAO [55], the higher yield level resulting from intensification of crop production and the use of modern varieties placed an additional burden on soil and fertilizer P supplies. Such productive crops are able to obtain more P from the field. Iqbal *et al*. [56] observed a marked response to P in different soil series of Pakistan. Tandon [57] also found wheat yield response to P were highest on low P alluvial soils and progressively lower on soil of higher soil fertility. Among major crops grown in sequence, wheat is more responsive to P application in low P soil and at lower level of P application. Brar *et al*. [58], Dhillon and Dev [59] and Kolar and Grewal [60] found similar wheat grain yield results in response to P application.

Sorghum fresh fodder yield: In Pakistan, major fodder crops during summer (kharif) include maize, sorghum and millets (rich in animal nutrition, succulent and palatable in pure stand), which are cut once after 50-60 days. The sorghum fodder yield depicted in Table 7 exhibit a maximum green fodder yield at T14 (residual P after wheat at solution P level of 0.5 mg L^{-1} plus P @ 13.65 mg kg^{-1}). The soil having residual phosphorus of 23.0 mg P kg^{-1} soil along with 13.65 mg P kg^{-1} added to sorghum, the maximum green fodder yield was 48.95 Mg ha^{-1}. The yield also increased significantly over native P solution (NK control). The reason for this might be that in comparing plant biomass systems for energy production, sweet sorghum is a leading contender due to its C_4 characteristics with a high photosynthetic rate and large biomass yield. The yield in control plot (0 NPK) was 18.09 Mg ha^{-1}. The results are in line with those of Bhatti [61] who obtained sorghum green fodder yield of 30.87 Mg ha^{-1} with traditional technology and 64.22 Mg ha^{-1} with improved technology and his data revealed that there was good compromise of fodder yield and fodder quality at 50% flowering stage of cutting. Khan *et al*. [62] compared green fodder yield of sorghum varieties in India (44.41 Mg ha^{-1}) with Pakistan (42.59 Mg ha^{-1}). In Pakistan, sorghum is more responsive to fertilizer without lodging due to its medium height, thicker stem, more leaves per plant and leaf area. The results also commensurate with those of Anees and Hassan [63] and Gill *et al*. [64] who emphasized adequate P fertilization to sorghum fodder on the basis of soil tests to get better yields. Phosphatic fertilizers are seldom applied to sorghum but it is an exhaustive crop and remove large amount of NPK. Kanwar [65] concluded that P response to sorghum varied across soil types and followed the order Alfisols>Entisols>Vertisols. Patidar and Mali [66] and Akmal and Asim [67] also obtained similar yield of the fodder.

Sorghum dry matter yield: The low yield of sorghum might be due to the reason, in general, that it is often grown on marginal lands and without P use. The availability of high yielding and fertilizer responsive varieties of sorghum has injected new enthusiasm in fertilizer research. It is important to assess the magnitude of their response to phosphorus levels and simultaneously find their production potential. The sorghum dry matter yield data are depicted in Table 7 which indicates significant improvement in growth of sorghum plants in ascending order of treatments i.e. lowest in T1 and maximum in T14. The role of P in modifying soil and plant environment is conducive for better growth. Maximum dry matter yield was achieved in T14. The maximum dry fodder yield was 10.72 Mg ha^{-1}. The yield in treatment where only NK was applied have significantly higher yield over control (without NPK). These results are in line with those of Das *et al*. [68] who observed that dry matter yield of sorghum increased with the application of P at all the stages of crop growth and boot leaf stage, response was observed up to 80 kg P_20_5 ha^{-1}. Hassan *et al*. [69] observed similar dry matter yield of sorghum which varied from 10.04 Mg ha^{-1} (Pakistan) to 15.39 Mg ha^{-1} (India). Patidar and Mali [66] found that stover yield of sorghum increased significantly (10.21 Mg ha^{-1}) upto 75% of recommended P level (30 kg P_2O_5 ha^{-1}). Akmal and Asim [67] also obtained similar results regarding dry matter yield of sorghum.

Rice paddy and straw yield: Phosphorus is the backbone of any fertilizer management program for intensive cropping system, which can remove up to 150 kg P_20_5 ha^{-1} annually [57]. Rice is a C_3 and semi aquatic plant that is commonly grown under flooded conditions in Pakistan. It can transport oxygen or oxidized compounds from the leaves to the roots and into the rhizosphere. The data regarding paddy and straw yield are presented in Table 7.

Table 8: Phosphorus concentration (%) in plant parts.

Treat-ments	Wheat			Sorghum	Rice		
	Booting	Grain	Straw	Fodder	Booting	Paddy	Straw
T1	0.09J	0.084L	0.010J	0.07K	0.07K	0.054J	0.024J
T2	0.09J	0.106K	0.016J	0.07K	0.08JK	0.064IJ	0.036IJ
T3	0.11I	0.151J	0.018J	0.10J	0.09IJ	0.074I	0.039HI
T4	0.12I	0.172I	0.028I	0.13I	0.10I	0.094H	0.049H
T5	0.14H	0.197GH	0.032I	0.15H	0.10HI	0.113GH	0.063G
T6	0.16G	0.190HI	0.042H	0.17G	0.12GH	0.121G	0.072FG
T7	0.18F	0.212G	0.051G	0.19F	0.13FG	0.147F	0.079F
T8	0.20E	0.246F	0.067F	0.22E	0.14EF	0.185E	0.099E
T9	0.21E	0.256EF	0.076E	0.24D	0.16DE	0.211D	0.106DE
T10	0.23D	0.277CD	0.087D	0.25C	0.17CD	0.242C	0.116CD
T11	0.25D	0.271DE	0.099C	0.29B	0.18C	0.255C	0.118BCD
T12	0.26C	0.293C	0.099C	0.31A	0.20B	0.259C	0.126BC
T13	0.32B	0.322B	0.108B	0.32A	0.21B	0.280B	0.130AB
T14	0.35A	0.348A	0.118A	0.32A	0.23A	0.301A	0.139A
LSD	0.014	0.019	0.008	0.008	0.019	0.020	0.012

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

It is obvious from the data that paddy and straw yield increased significantly in ascending order of treatments which were from T3 to T14 (residual P in respective plots after sorghum plus P @ 19.65 mg kg^{-1}). Maximum response was obtained at T10. The soil had residual phosphorus of 10.05 mg P kg^{-1} soil along with 19.65 mg P kg^{-1} applied to rice. This indicated that though soils were high P fixing but the residual responses were achieved at T10 and it might be due to the reason that under submerged conditions, solubility of adsorbed/fixed P is increased. Phosphorus application promoted plant growth through an adequate supply and helped in better development of roots. Intensive cropping has drastically reduced native soil fertility to such an extent that addition of fertilizers has become necessary to increase and maintain crop yields. These results are supported by the work of Nelson [70] who reviewed that on soils low in active P or total P, sufficient P might not become available and response to P fertilization could be observed. Khan and Makhdum [20] concluded in a study that optimal level of P for rice was 6.59 mg kg^{-1} under irrigated conditions and response is dependent on initial P status of soil. Pradhan and Mondal [71], Chandra *et al*. [72], Nadeem and Ibrahim [73] and Slaton *et al*. [74] also found similar results.

Phosphorus concentration (%) in plants

Phosphorus concentration (%) in wheat plants at booting stage: Since the P concentration in a plant reflects the adequacy of P for plant growth and many useful yield-P concentration relationships have been developed to serve as a guide for recommending P fertilizer use. Phosphorus concentration in wheat plants at booting stage is depicted in Table 8 which indicated that increase in P solution level raised the P concentration in plants significantly but considering the 0.2 % P as sufficient, it was attained at 0.10 mg P L^{-1} solution which was obtained by adding 137.95 kg P_2O_5 ha^{-1}. However, the higher levels showed a luxury consumption of P at this stage. Tandon [57] stated that modern high yielding grain varieties continue to absorb P till maturity and almost 70-80% of absorbed P ends up in the spikes or panicles. During early stages of plant growth, P accumulation can proceed faster than dry matter production indicating the need for higher P concentration for active vegetative growth and root proliferation, which is to follow setting of basic infrastructure for yield production. Phosphorus concentration below 0.05 mg P L^{-1} is in the deficient range indicating that wheat roots were unable to absorb sufficient P from soil solution below these levels for good crop growth. Similar results were reported by Alam [75] for increasing effect of P fertilizer on P concentration in wheat plant. The results also corroborates with the findings of Fageria *et al*. [76]; Gill *et al*. [77]; Bahl and Singh [78]; Singh *et al*. [79] and Delong *et al.* 80].

Phosphorus concentration (%) in wheat grain and straw: Phosphorus concentration in plant can be related to phosphorus extraction power of roots from soil. Normally plant roots having wider contact with soil are better extractor of phosphorus from soil and feed well to above ground plant parts. This is true for extensive root system [81]. Adequate phosphorus concentration in wheat grain is 0.42% [82]. The data regarding P concentration in grain and straw are shown in Table 8. The data revealed that different soil solution levels of P had significant effect on P concentration in wheat grain and straw. Maximum P concentration was obtained at 0.50 mg P L^{-1} (developed by adding 316.02 kg P_2O_5 ha^{-1}) both in grain and straw. Minimum P concentration was observed in the treatment where no P was applied. Each increment of P in soil solution progressively increased the P content of the grain and straw with few exceptions. However the P concentration in wheat straw was much less than that in grain due to the reason that phosphorus taken up by the plants by vegetative parts (straw) was shifted to the reproductive parts (grain) after fertilization. Singh *et al*. [79] observed grain yield and seasonal accumulation of P by wheat were higher for higher P rates. The results are supported by the findings of Alam [75]; Hassan *et al*. [69]; Brar [58] and Delong *et al*. [80].

Phosphorus concentration (%) in sorghum fodder: The phosphorus concentration of forage crops is important since low P content in the animal diet leads to “aphosphorosis” which is a serious disease in livestock. At less extreme levels of P deficiency, the fertility of livestock may be quite seriously affected [55]. Data regarding P concentration in sorghum fodder depicted in Table 8 show that maximum P concentration (0.32%) at T13 (residual P 21.95 mg kg^{-1} + 13.65 mg kg^{-1} added P). Minimum P concentration was observed in the control plot where no NPK were applied. As the sorghum is a C_4 plant and has extensive deep root system that can explore larger volume of soil for P extraction. Similar results were found by Buah *et al*. [82]; Alvarez *et al*. [84]; Meelu *et al*. [85] and Niraj *et al*. [86].

Phosphorus concentration (%) in rice at booting stage: Nutrient concentration (content per unit dry weight) is often used to assess soil nutrient deficiency and toxic levels. Data regarding P concentration at booting stage depicted in Table 8 indicate that it was maximum in T14. The maximum level of P concentration was 0.23% in the rice plants. Minimum P concentration was observed at native soil solution level of P, which was 0.07% and being in deficient range (Olsen P 4.95 mg kg^{-1}) showing that soil was quite deficient in available P, although the diffusion rate is always greater under submerged conditions.

Phosphorus concentration (%) in paddy and straw: Data regarding P concentration in paddy and straw is depicted in Table 8. At a glance on data, it was seen that maximum P concentration was examined in paddy and straw grown under T14. Minimum P concentration was found in the control plots where no NPK fertilizer was added. The data also revealed that sufficiency level of 0.20% was achieved in T9 (residual P 9.50 mg kg^{-1} + 19.65 mg kg^{-1} added P), which leads to the conclusion that the crop roots extracted residual P in a better way. There is no consistent relationship among P concentration in the various tissues of the rice plant. Fageria [87] described sufficient P range in rice paddy as 0.26 and 0.06% in straw while PPI [82] described it as 0.28% in paddy and 0.09% in straw. Similar results were found by Singh *et al*. [79] who found mean P content of rice grain from 20 soil series ranging from 0.41 to 0.55% respectively. Slaton *et al*. [74] found mean grain P concentration of 0.28% at Brooks-97, 0.33% at Davis-97, 0.29% at Wimpy-97, 0.26% at Davis-98 and 0.31% at Wimpy-98 and the concentration of P in the grain at

Table 9: P uptake (kg ha^{-1}) by different crops

Treatments	Wheat Grain	Wheat Straw	Wheat Total	Sorghum Total	Rice Paddy	Rice Straw	Rice Total
T1	1.30K	0.12J	1.42N	2.65M	0.93L	0.63J	1.56L
T2	2.55J	0.28J	2.82M	3.04LM	1.20L	0.72J	1.92L
T3	3.39I	0.38IJ	3.77L	4.46L	1.84K	0.94IJ	2.78K
T4	4.46H	0.73HI	5.19K	6.54K	2.60J	1.28I	3.88J
T5	5.74G	0.95H	6.66J	8.63J	3.53I	1.81H	5.34I
T6	6.37G	1.40G	7.77I	10.50I	4.11H	2.31G	6.42H
T7	7.56F	1.88F	9.44H	12.77H	5.39G	2.84F	8.23G
T8	9.14E	2.63E	11.76G	15.96G	7.09F	3.65E	10.74F
T9	9.73E	3.06D	12.79F	18.56F	8.74E	4.02E	12.76E
T10	10.73D	3.64C	14.38E	21.20E	10.60D	4.62D	15.22D
T11	11.23D	4.32B	15.56D	25.65D	11.37C	4.98D	16.35C
T12	12.41C	4.34B	16.76C	29.86C	12.58B	5.55C	17.08C
T13	13.83B	4.80A	18.63B	32.04B	12.43B	6.26B	18.69B
T14	14.79A	5.12A	19.91A	34.67A	13.39A	7.05A	20.44A
LSD	0.6920	0.3936	0.8656	1.499	0.5591	0.4179	0.7908

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

3 week after 50% heading or physiological maturity was about twice than that of the rice straw. Nelson [70] also reported similar results.

Phosphorus uptake (kg ha^{-1})

Phosphorus uptake (kg ha^{-1}) by wheat grain and straw: Uptake of P is most rapid in wheat from joining stage to anthesis complete growth stages and 75% of the P uptake is translocated to the grain at maturity [87]. Data regarding P uptake by wheat grain and straw depicted in Table 9 showed that maximum uptake of P was noted at 0.50 mg P L^{-1} soil solution and this level was developed by adding P fertilizer @ 316.25 kg P_2O_5 ha^{-1}. Minimum P uptake was seen by wheat grown in the control (without NPK) and each additional level of P had profound effect on its uptake. It is stated that the amount of P removed on an average yield of harvested grain varies from 7-15 kg P ha^{-1} (16-34 kg P_2O_5 ha^{-1}) and from this; 2-8 kg P ha^{-1} is returned back to the soil in the form of crop residues, which are left in the field [88]. The present results are supported with the findings of Goudong *et al*. [89] who reported an increase in P uptake with increase in P supply. Alam *et al*. [90]; Zade *et al*. [91]; Iqbal [92]; Latif *et al*. [93] and Delong *et al*. [80] also reported similar findings.

Total phosphorus uptake (kg ha^{-1}) by wheat: Phosphorus uptake by grain and straw of wheat is collectively known as total phosphorus uptake by wheat. The amount of total P uptake by wheat depends upon the production level, amount of applied P i.e. solution level and soil type. Total P uptake by wheat is presented in Table 9 which revealed that maximum P uptake by wheat (19.91 kg ha^{-1}) was noted at T14 i.e. 0.50 mg P L^{-1} solution level which was obtained by adding 316.02 kg P_2O_5 ha^{-1} and was found significantly different with T13 (developed by adding 281.75 kg P_2O_5 ha^{-1}). Minimum P uptake was seen in control plot (without NPK), which was 1.44 kg ha^{-1}. FAO [55] pointed out that P removal by wheat with an average yield of 3 Mg ha^{-1} is 27 kg P_2O_5 ha^{-1} and 5 Mg ha^{-1} remove 60 kg P_2O_5 ha^{-1}. Alam [75] also showed that the application of 25 mg P kg^{-1} soil significantly increased the dry matter, straw and grain yields as well as total P uptake by wheat crop. Fageria *et al*. [76]; Gill *et al*. [77, 64]; Goswami and Baroova [94]; Yaseen *et al*. [95]; Alam *et al*. [96] and Latif *et al*. [93] also observed similar results.

Phosphorus uptake (kg ha^{-1}) by sorghum fodder: Phosphorus uptake by sorghum fodder is product of fodder yield and concentration of phosphorus in fodder. The data regarding P uptake by sorghum fodder is given in Table 9. The maximum P uptake (34.67 kg ha^{-1}) was recorded at T14 (residual P 23.00 mg kg^{-1} + added P 13.65 mg kg^{-1}) and was significantly more than T13 (residual P 21.95 mg kg^{-1} + added P 13.65 mg kg^{-1}). This P uptake was found minimum in control plot (without NPK) and was 3.96 kg ha^{-1}. The data also showed that P uptake was progressively increased with increasing treatment numbers from T1 to T14.

Phosphorus uptake (kg ha^{-1}) by rice paddy and straw: Phosphorus uptake by paddy and straw is product of paddy or straw yield and concentration of phosphorus in paddy or straw. The data regarding P uptake by rice paddy and straw is given in Table9. The data showed that maximum P uptake by paddy and straw was recorded at T14 (residual P 13.75 mg kg^{-1} + added P 19.65 mg kg^{-1}) and was significantly better than T13 (residual P 12.85 mg kg^{-1} + added P 19.65 mg kg^{-1}) and T12 (residual P 11.70 mg kg^{-1} + added P 19.65 mg kg^{-1}), which were nonsignificant with each other. This P uptake was found minimum in control plot (without NPK). The increase in P uptake was increased with the increase in corresponding rates of P application.

Total phosphorus uptake (kg ha^{-1}) by rice: Total phosphorus uptake by rice crop is the combined value of P uptake by paddy and straw. The data regarding total P uptake by rice crop is given in Table 9. The data showed that maximum P uptake by rice crop (20.44 kg ha^{-1}) was recorded at T14 (residual P 13.75 mg kg^{-1} + added P 19.65 mg kg^{-1}) and was significantly better than T13 (residual P 12.85 mg kg^{-1} + added P 19.65 mg kg^{-1}). The total P uptake was found minimum in control plot (without NPK) and was 2.14 kg ha^{-1}. The increase in P uptake was increased with the increase in corresponding rates of P application and there was a significant increase in P uptake with the increasing treatment numbers ascendingly.

Phosphorus requirement of crops under field conditions: The phosphorus requirement of wheat, sorghum fodder and rice crops were determined on the basis of near maximum (95% of the attainable maximum yield) crop yield. The fertilizer requirements are crop specific and site specific and can be estimated as internal and external P requirements. Fox [13] reported that phosphorus requirement, both internal and external, of most crops were greater during early stage of growth than for crops approaching to maturity.

Internal phosphorus requirement of wheat: The term "internal P requirement" can be defined as the concentration of phosphorus in the diagnostic plant part associated with near maximum (95%) yield. The internal requirement generally parallels, but is not identical with the "critical concentration" and is reflection of available nutrient status in soils. For wheat, internal P requirement was determined at two stages i.e. at booting stage and at crop maturity in grain.

Internal phosphorus requirement of wheat at booting stage: The phosphorus concentration in wheat plants at booting stage was plotted against relative yield of wheat grain by Boundary Line Technique [97] and is shown in Fig. 4 (i). The value of P concentration (%) for 95% relative yield was determined by regression equation and the value obtained was 0.249%, which was critical phosphorus concentration for 95 % of maximum wheat yield at booting stage. The results are in line with those of Memon and Fox [98] who demonstrated that phosphorus content of two wheat varieties (Pak-70 and Pavan) increased at flag leaf stage as the phosphorus concentration in the solution increased. Rashid *et al.* [99] found internal P requirement of crops in whole shoots (<30 cm tall) as 0.23% for maize, 0.26% for chickpea, 0.27% for mustard, 0.28% for wheat and lentil, 0.29% for sunflower and 0.30% for mungbean. Rehman *et al*. [100] said that the critical phosphorus concentration ranged from 0.22 to 0.26% for 40-60 cm tall maize plants. Similarly Chaudhry *et al*. [31] determined 0.22% as internal P requirement of maize for 95% maximum yield.

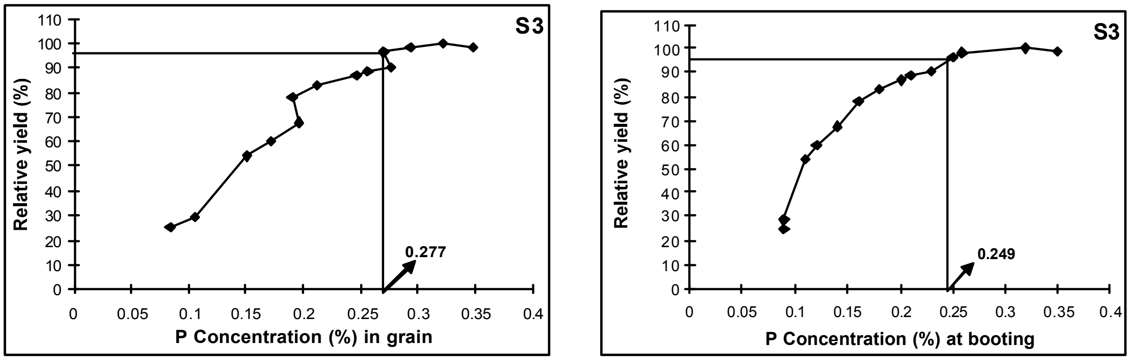
Internal phosphorus requirement of wheat at maturity: Internal requirement of wheat was determined by making graph of P concentration in grain and maximum attainable 95% relative yield as shown in Fig. 4 (ii). The value obtained was 0.277%. This means that as the crop passed through reproductive phase, the phosphorus that is highly mobile within the plant was shifted to the seed and this transfer of P was very rapid. Rashid *et al.* [101] found critical P concentration in wheat grain as 0.22% and in maize grain as 0.27% under green house conditions.

Internal phosphorus requirement of sorghum fodder: Sorghum is a C_4 plant whose photosynthetic efficiency is very high and the internal requirement of P of sorghum fodder which is dependent on the P concentration at maximum growth (vegetative) was determined and plotted as shown in Fig. 5. The graph revealed that maximum internal P requirement of 0.326% was found for sorghum in this soil. Similar results were reported by Rehman *et al*. [100] and Chaudhry *et al*. [31]. Rashid *et al*. [99] also found internal P requirement of crops in whole shoots (<30 cm tall) as 0.23% for maize, 0.26% for chickpea, 0.27% for mustard, 0.28% for wheat and lentil, 0.29% for sunflower and 0.30% for mungbean.

Internal phosphorus requirement of rice at booting stage: Data regarding P concentration at booting stage of rice was plotted against 95% relative yield of rice as shown in Fig. 6 (i) which illustrates that internal P requirement of rice was 0.165%. The reason for low critical P (%) in rice than that in wheat and sorghum might be due to greater solubility and diffusion of P under flooded conditions and plant at early stages upto booting stage absorbed P very efficiently from the soil solution.

Internal phosphorus requirement of rice at harvest: The plot of P concentration in paddy versus 95% relative paddy yield is shown in Fig. 6 (ii) which revealed that maximum internal P requirement of 0.220% was found for rice in this soil..

External (Olsen) phosporus requirement of wheat: Data regarding 95% relative yield of wheat was plotted against Olsen P in the soil after wheat harvest as shown in Fig. 7



i) At booting stage ii) At harvest

Fig. 4: Internal P requirement of wheat

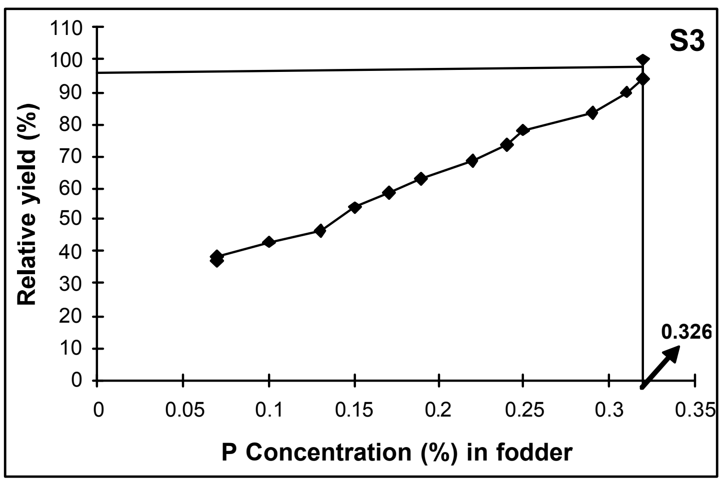
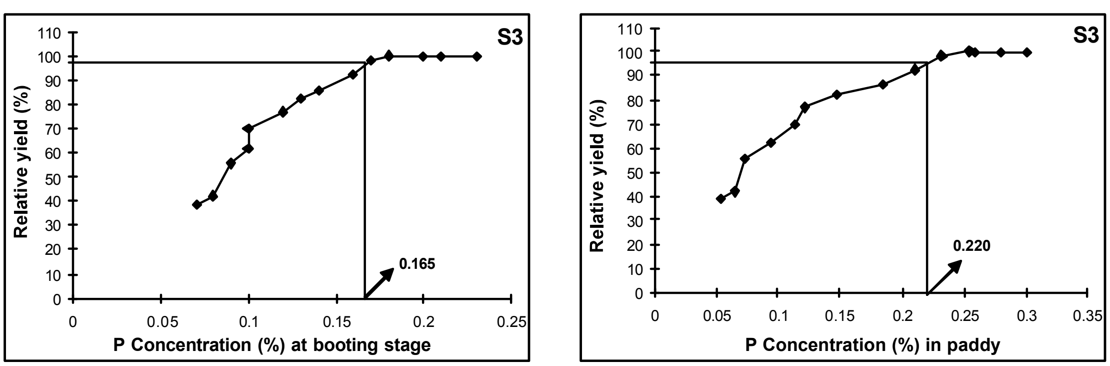


Fig. 5: Internal P requirement of sorghum fodder



i) t booting stage ii) At harvest stage

Fig. 6: Internal P requirement of rice

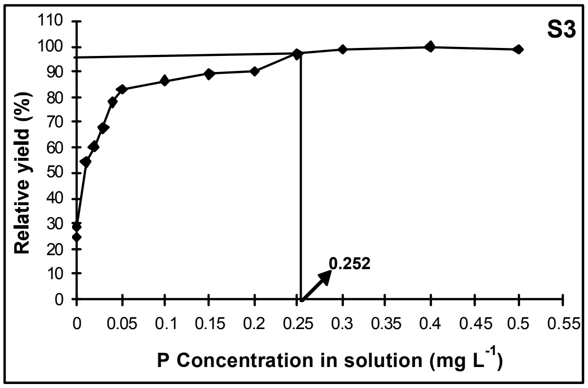
(I). A glance on the graph illustrate that the external P requirement for wheat was 13.80 mg kg^{-1} in this soil. The critical limits are defined as; Olsen P<5 mg kg^{-1} as deficient, 5-10 mg P kg^{-1} as satisfactory and >10 mg P kg^{-1} as adequate, qualifies for this data very well. Rashid *et al*. [101] determined fertilizer requirement for near maximum wheat grain yield as 15 mg P kg^{-1} soil. Rehman *et al*. [100] determined 16 mg P kg^{-1} soil as Olsen P a critical level for 95% relative yield of wheat in Malakand division. Memon *et al*. [102] reported that crop response experiments adequately established P deficiency (<10 mg kg^{-1} Olsen P) in the majority (>90%) of Pakistan soils. Khan and Makhdum [20] found 7.19 mg P kg^{-1} as critical concentration for near maximum grain yield of wheat. Bhatti *et al*. [103] found 13 mg kg^{-1} as critical level of P in soil for wheat. Memon [54] found 20 kg and 19 kg P ha^{-1} was required to obtaine 95% maximum yield at Tandojam and Tarnab, respectively. Nisar [104] reported that for getting 95% relative yield, 75, 92, 114 and 150 kg P_2O_5 ha^{-1} was required for the Lyallpur, Gujranwala, Hafizabad and Sultanpur series, respectively. Khan and Rafiq [105] also found 150 and 100 kg P_2O_5 ha^{-1} as optimal dose for wheat grain on the rasulpur and hafizabad soils which are moderately calcareous.

External (solution) phosphorus 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 [97] as shown in the Fig. 7 (ii). The graph revealed that solution P requirement of 0.252 mg P L^{-1} was required for 95% yield in this soil. Memon *et al*. [106] 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 but the concentrations which have been shown by many workers to be 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 [107]. Similarly, Beckwith [8] suggested a standard concentration of 0.2 ug P mL^{-1} as adequate for most plant species. Memon [54] showed that P solution associated with 95% maximum yield of wheat was 0.025 ug mL^{-1}, particularly 0.029 ug mL^{-1} for Pak-70 and 0.023 ug mL^{-1} for pavon variety. Memon *et al*. [106] determined external P requirement of wheat grain at near maximum yield as 0.032 mg L^{-1} as obtained from composite yield response curve. Hassan *et al*. [29] calculated P fertilizer requirement using sorption isotherms as 83, 51, 50 and 8 mg P kg^{-1} for the Missa, Gujranwala, Abbotabad and Risalpur soil series to adjust soil solution P level of 0.2 mg P L^{-1} and Soil solution P requirement of corn for near maximum (95%) biomass production was 0.3 mg P L^{-1}. Nisar [104] reported that P solution values for Lyallpur, Gujranwala, Hafizabad and Sultanpur series were found to be 0.09, 0.052, 0.26 and 0.90 mg L^{-1} for attaining 95% of maximum wheat yield and using the composite response curve, the P in solution was found to be 0.35 mg L^{-1}.

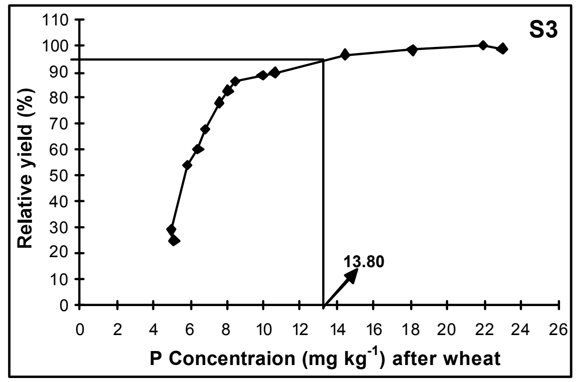
External (Olsen) phosphorus requirement of sorghum fodder: Olsen P as determined after harvesting sorghum fodder was plotted versus 95% relative yield to determine the external Olsen P requirement as shown in Fig. 8. Maximum relative yield was obtained at Olsen P of 12.68 mg P kg^{-1} in this soil. The reason might be that growth of sorghum was quite rapid at early stages of growth and buffering capacity of the soil was very high, so higher P is replenished in soil solution (Quantity intensity factor) in this soil. Jones and Benson [108] showed that the relationship between percent P in leaves of corn at pre tasseling stage and P concentration of equilibrium soil extracts was linear.

External (Olsen) phosphorus requirement of rice: Data regarding Olsen P concentration after rice was plotted against 95% relative yield to find out the external Olsen P requirement of rice and the graphs are presented in Fig. 9. It was found that Olsen P requirement for near maximum yield of rice paddy was achieved at Olsen P of 10.05 mg P kg^{-1} in the soil. The reason might be the submerged soil conditions under which rice crop grow and the P availability remained at par as compared to the upland or oxidized conditions. Khan and Rafiq [105] found 16 mg kg^{-1} Olsen P as critical level for 95% relative yield of rice. Khan and Makhdum [20] determined critical level of P for near maximum yield of rice as 7.19 mg kg^{-1}.

Phosphorus availability status in soils after wheat harvest: It is widely recognized that the efficiency of applied P increases if P application rates are tailored to the initial P fertility of the soil. After the harvest of wheat, soil samples were collected from all the plots and analyzed for

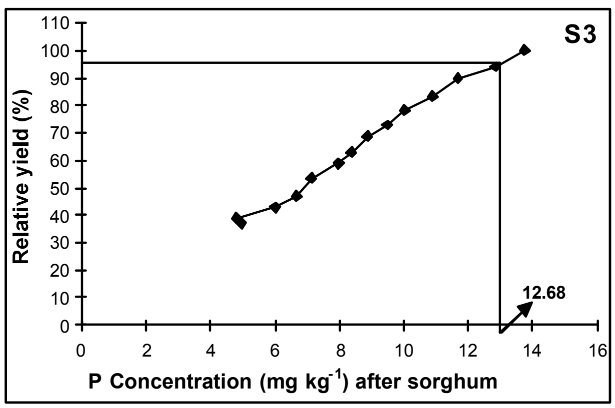


i) Olsen P (mg kg^{-1})



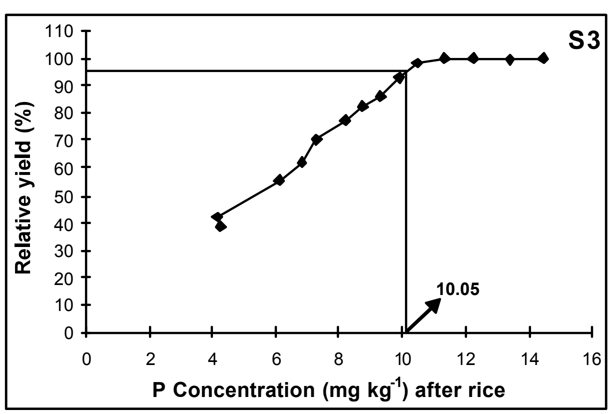
ii) Solution P (mg L^{-1})

Fig. 7: External P requirement of wheat



Olsen P (mg kg^{-1})

Fig. 8: External P requirement of sorghum fodder



Olsen P (mg kg^{-1})

Fig. 9: External P requirement of rice

Table 10: Olsen extractable P (mg kg^{-1} soil) after harvest

Treatments	Wheat	Sorghum	Rice
T1	5.10M	4.95H	4.65M
T2	5.00M	4.80I	4.45M
T3	5.90L	6.00H	6.15L
T4	6.45K	6.65H	6.85K
T5	6.85J	7.10GH	7.30J
T6	7.60I	7.95FG	8.20I
T7	8.05H	8.40F	8.75H
T8	8.45G	8.90EF	9.30G
T9	9.95F	9.50DE	9.90F
T10	10.60E	10.05CD	10.50E
T11	14.40D	10.90BC	11.35D
T12	18.10C	11.70B	12.25C
T13	21.95B	12.85A	13.40B
T14	23.00A	13.75A	14.50A
LSD	0.2123	1.041	0.2489

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

Olsen P to determine the P status. The data presented in Table 10 reveal that P application rates significantly increased the available P status 5.90 to 23.00 mg kg^{-1} in the soil. However the native P status decreased in all the soils (5.20 to 5.10 mg kg^{-1} where no fertilizer was applied and where NK was applied, this native P further decreased to 5.00 mg kg^{-1}.

Decline in available P without P application is understandable because there is only P output without any input. Similarly Tandon [57] summarized the results of 18 experiments and concluded that when half of the optimum rates of P were used, available P declined or showed little change at 60% sites and when applied optimum rates of P, a significant improvement in available P status was found. It was observed in the present study that to raise P fertility to a given level, different amounts of P are required. It was also noted that the higher P rates become uneconomical for resource-constrained farmers. Phosphorus availability status in soils after sorghum fodder harvest

Data regarding available phosphorus status in soil after harvesting sorghum fodder are presented in Table 10 which showed that soil P status which was built after the wheat decreased to some extent with the passage of time and contributed to the P uptake by plants or adsorption on soil. Native P of soils decreased to 4.65 mg kg^{-1} in control plots of soil while in the plots receiving NK, Olsen P was further reduced to 4.80 mg kg^{-1}. However, the overall status of soil available P ranged from 6.00 to 13.75 mg kg^{-1} in this soil. The results are in line with that of Tandon [57] who described that the continuous application of recommended levels of P resulted in a significant increase in the soils available P status.

Phosphorus availability status in soils after rice harvest: Available phosphorusdetermined after harvesting of rice is depicted in Table 10 which revealed that soil P status was little bit improved after rice crop. The possible reason might be that the rice was grown under submerged conditions and more phosphorus became available for plant uptake and this P availability status reflected that wetting and drying conditions changed the available P status of soil i.e. after wheat it was built up due to high P application, after sorghum it decreased and after rice, it either maintained or slightly increased. The native P status decreased to 4.65 mg kg^{-1} in the plot where no NK was applied and where NK was applied, it further reduced to 4.45 mg kg^{-1} in the soil. These data confirmed that where no fertilizer was given, the rate of P depletion was less as compared to that where NK fertilizer was added. The application of NK improved the growth and increased root growth extracted more P from the native source. Tandon [57] pointed out that soils which are medium to high in available P, when cropped using N alone become deficient in P within a couple of years and yields drop drastically unless P fertilizers are applied. Similar results were obtained with rice [109] and a number of intensive crop rotations [110]. Katyal [111] found that alluvial soils are most vulnerable to depletion of P and accentuation of P deficiencies as a result of imbalanced fertilization with rice. Tandon [57] also determined that alluvial soil built up to 73 kg P_2O_5 ha^{-1} of available P could sustain only 3 successive harvests of maize-wheat-maize cropping without P application.

Phosphorus fertility build-up factor and level of phosphorus build-up: The data regarding phosphorus fertility build-up factor (PFBF) and the level of P build-up is presented in Table 11 which exhihibited that PFBF was maximum (44.74) in T3 (0.01 mg P L^{-1}) and minimum (11.00) in T14 (0.50 mg P L^{-1}) with a mean value of 18.51.

As regards level of P build-up, the maximum value (0.091 mg kg^{-1}) was achieved in T14 (0.50 mg P L^{-1}) and minimum value (0.022 mg kg^{-1}) in T3 (0.01 mg P L^{-1}) with mean value of 0.054 mg kg^{-1}. There was a net decrease in control plots @ 0.144 mg kg^{-1} in NPK check and

Table 11: Phosphorus fertility build-up factor (PFBF) and level of P build-up

	P added (mg kg^{-1})							
Treatment No.	Wheat	Sorghum	Rice	Total P (mg kg^{-1})	Olsen P-Native P	Net available P	PFBF	Level of P build-up
T1	0	0	0	5.20	4.45-5.20	-0.75	0	-0.144
T2	0	0	0	5.20	4.35-5.20	-0.85	0	-0.164
T3	9.20	13.65	19.65	42.50	6.15-5.20	0.95	44.74	0.022
T4	13.15	13.65	19.65	46.45	6.85-5.20	1.65	28.15	0.036
T5	16.20	13.65	19.65	49.50	7.30-5.20	2.10	23.57	0.042
T6	18.79	13.65	19.65	52.09	8.20-5.20	3.00	17.36	0.058
T7	21.08	13.65	19.65	54.38	8.75-5.20	3.55	15.32	0.065
T8	30.12	13.65	19.65	63.43	9.30-5.20	4.10	15.47	0.065
T9	37.12	13.65	19.65	70.42	9.90-5.20	4.70	14.98	0.067
T10	43.05	13.65	19.65	76.35	10.50-5.20	5.30	14.41	0.069
T11	48.29	13.65	19.65	81.59	11.35-5.20	6.15	13.27	0.075
T12	53.04	13.65	19.65	86.34	12.25-5.20	7.05	12.25	0.082
T13	61.51	13.65	19.65	94.81	13.40-5.20	8.20	11.56	0.087
T14	69.00	13.65	19.65	102.30	14.50-5.20	9.30	11.00	0.091
Mean							18.51	0.054

@ 0.164 mg kg^{-1} in P check plots, respectively. Similar results were obtained by Tandon [57] and Puno [21]. Harapiak and Beaton [112] found that crops often absorb less than 20% of fertilizer P during first cropping season after application and level of soil P gradually rises contributing more to available phosphous pool for growing plants.

CONCLUSIONS

Main conclusions drawn from this piece of study are as under

1. Phosphatic fertilizers should be recommended and applied to the crops by taking P adsorption capacities into the account and P application should be soil and crop specific as the solution P and Olsen P vary for the soils and crops.
2. Olsen P can be built-up for any desired level in the soils considering the phosphorus fertility build-up factor (mg P required to build 1 mg P kg $^{-1}$ soil).
3. External P requirement was greater for sorghum fodder being heavy P feeder followed by rice and wheat. External P requirement showed significant correlation with 95% relative yield of wheat, sorghum fodder and rice. However higher P rates needs to be tested for sorghum fodder for getting maximum yields.
4. Taking plant samples at booting stage than at crop maturity for obtaining 95% relative yield better correlated internal P requirement of crops.
5. Soils are being mined per annum @ 0.144 mg P kg^{-1} if no fertilizers are applied and @ 0.164 mg P kg^{-1} if only NK are applied in fine textured soils, respectively. So balanced fertilization is a pre-requisite for harvesting maximum crop yields.

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