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Effect of Integrated Application of Phosphorus and Sulphur on Yield and Micronutrient Uptake by Chickpea (*Cicer arietinum*)

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ABSTRACT

Field experiments were conducted at two different locations (Barani Agricultural Research Institute Chakwal & farmer's field Talagang, district Chakwal) in northern rainfed Punjab, Pakistan to assess the yield and micronutrient uptake of chickpea (*Cicer arietinum* L.). The treatments comprised of three levels (0, 40 & 80 kg P_2O_5 ha^{-1}) of phosphorus (P) and three levels (0, 15 & 30 kg ha^{-1}) of sulfur (S) in different combinations. Application of P and S resulted in significant increase in grain yield ranging from 22 to 35% and 10 to 16% over control, respectively. Effect of P and S application was synergistic at all P and S levels at Barani Agriculture Research Institute (BARI) Chakwal, while at farmer's field Talagang, it was synergistic at lower level of P application (40 kg ha^{-1}) and antagonistic at higher level of P (80 kg ha^{-1}). Lower level of P application (40 kg ha^{-1}) resulted in increase in zinc (Zn) uptake by 23 to 25% over control and higher rate (80 kg ha^{-1}) caused decline in Zn uptake. Almost similar observations were recorded regarding effect of S application on Zn uptake in both grain and straw. Both P and S application resulted in increase in copper (Cu) uptake by 40 to 62% and 16 and 59%, respectively. There was 21 to 74 and 19 to 70% increase in iron (Fe) uptake with application of P and S, respectively. Corresponding figure for manganese (Mn) uptake was in range of 17 to 34% for P and 14 to 42% for S.

Key Words: Sulfur; Phosphorus; Chickpea; Grain yield; Biological yield; Micronutrient uptake

INTRODUCTION

Chickpea is an important pulse crop of rainfed areas in semiarid/arid climate. Average chickpea yield in Pakistan is 785 kg ha^{-1} (Govt. of Pakistan, 2007), which is very low compared with developed countries of the world such as China (4135 kg ha^{-1}), Canada (1427 kg ha^{-1}) and USA (1391 kg ha^{-1}) (FAO, 2005). This low yield is due to a number of genetic, agronomic and environmental factors and imbalanced fertilization is the key among them (Idris *et al.,* 1989).

Sulfur does interact with phosphorus as phosphate ion is more strongly bound than sulphate (Hedge & Murthy, 2005). Phosphorus fertilizer application results in increased occupation of anion adsorption sites by phosphate, which then releases sulphate ions into the soil solution (Tiwari & Gupta, 2006). Thus, it may be subjected to leaching if not taken up by plant roots. There exists a synergistic relationship between P and S at low level of S application and antagonistic relationship at higher level of S application in wheat (Randhawa & Arora, 2000). Likewise, Pandey *et al.* (2003) also observed synergistic relationship between two nutrients in linseed. Nonetheless, sulfur and phosphorus interaction was negative in lentil and chickpea (Hedge & Murthy, 2005). Hence, nature of interaction of two nutrients depends on initial soil fertility status, rate of nutrients applied and the crop species.

Both S and P are known to interact with almost all essential macronutrients, secondary nutrients and micronutrients (Abdin *et al.,* 2003). Application of S containing fertilizer can result in soil acidification and eventually may influence nutrient uptake (Havlin *et al.,* 2007). In chickpea grown under green house conditions, application of 100 mg P kg^{-1} resulted in increased uptake of Zn, Cu, Fe and Mn but decreased the concentration of Ca and Mg in the plant tissues (Tufemkci *et al.,* 2005). There was negative relation between P and Zn concentration in tea seedlings when P application was varied from 0 to 35 mg P kg^{-1} (Bakhshipour *et al.,* 2008). A synergistic effect of applied S and Fe was also reported (Malewar & Ismail, 1997). Application of 10 mg Fe kg^{-1} improved its availability by 10%, where as 80 mg S kg^{-1} enhanced it by 49%. Combined application of both nutrients resulted in tremendous boost in Fe availability by 101%. A close relationship was observed between Fe and S in plant metabolism (Malewar & Ismail, 1997).

In India, a number of studies have been conducted regarding effect of S on yield of leguminous crops and on an average 22% increase in yield of legume crops (chickpea, pigeonpea, lentil, pea, urd bean, ground nut) has been recorded (Shrinivasarao *et al.,* 2004; Raina & Tanawade, 2005). While in European countries, mostly work is focused on peas (*Pisum sativa* L.) and 78% yield increase has been reported in pot experiments (Scherer *et al*., 2006).

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In Pakistan, work done regarding crop response to S application is limited to oilseeds and their oil contents only (Manaf & Hassan, 2006; Hassan *et al.,* 2007a; Hassan *et al.,* 2007b). Research work regarding interaction of P and S and their role in legumes growth and nutrient uptake is very rare. Therefore, present study was conducted to assess the interactive effect of sulfur and phosphorus application on yield and micronutrient (Zn, Fe, Mn, Cu) uptake by chickpea crop under rainfed conditions of northern Punjab, Pakistan.

MATERIALS AND METHODS

Field experiments were conducted using Chickpea cultivar Balkassar 2000 at BARI, Chakwal (32.5° N latitude, 72.4° E longitude) and Farmer's field Talagang, district Chakwal (32.5° N latitude, 72.2° E longitude) during 2006-07. The details of physical and chemical properties of soil at start of experiment are presented in Table I. The trial was laid out in randomized complete block design with split plot arrangement (1.5 ×3.5 m plot at BARI Chakwal & 1.8 × 4 m farmer's field Talagang) keeping P in main plots and S in subplots. There were nine treatments having different combinations of P (0, 40, 80 kg ha^{-1}) and S rates (0, 15, 30 kg ha^{-1}). Starter dose of nitrogen (26 kg ha^{-1}) was applied in the form of urea in all treatments except those receiving nitrogen from ammonium sulphate. Phosphorus was applied in the form of triple super phosphate (TSP) and S through Ammonium Sulphate. All the treatments were replicated three times. The treatments comprising of different combinations of P and S are shown in Table II. Chickpea crop was sown on 13-10-2006 and 15-10-2006 at BARI Chakwal and farmer's field Talagang, respectively maintaining row to row distance of 30 cm. All the fertilizers were applied as basal dose. Crop was grown under rainfed conditions and no supplemental irrigation was applied. Harvesting was done on 02-05-2007 and 03-05-2007 at BARI Chakwal and farmer's field Talagang, respectively. Crop from an area of one meter square in the middle of each plot was harvested separately. The plant samples were dried and data was recorded for grain and biological yield. Representative samples of 100 g for both straw and grain separately, were collected from bulk sample, oven dried and ground. Micronutrients (Zn, Cu, Fe & Mn) were determined by atomic absorbtion spectrometer (model GBC-932 plus) from the filtrate obtained after dry ashing (Chapman & Pratt, 1961). Data on all observations were subjected to analysis of variance (ANOVA) by using software MSTATC. Treatment means were compared by Duncan multiple range (DMR) test. Regression analysis was also done to quantify the effect of treatments on yield and nutrient uptake and to compare the response at two sites.

RESULTS

Seed yield. Effect of P and S application on chickpea seed yield was significant at BARI Chakwal (Table III). Highest seed yield (1422 kg ha^{-1}) was recorded for plot having treatment P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}) followed by P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}) and P_2S_2 (80 kg P_2O_5 & 30 kg S ha^{-1}), which differed significantly from P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}) but were at par with each other. Sole application of P (40 & 80 kg ha^{-1}) and S (15 & 30 kg ha^{-1}) resulted 34 and 35% and 12 and 14% increase in yield over control, respectively.

At farmer's field Talagang, interaction of P (40 & 80 kg ha^{-1}) and S (15 & 30 kg ha^{-1}) was non significant but their individual effects were significant resulting in an increase in seed yield by 22 and 32 and 10 and 16% over control, respectively. Regression analysis shows that response to unit application of P and S was higher at farmer's field Talagang as compared to BARI Chakwal (Table XIII).

Biological yield. Almost similar results were recorded for both locations regarding biological yield. Individual effect of P and S application was significant on biological yield but their interaction was non significant (Table IV). Phosphorus application (40 & 80 kg ha^{-1}) resulted in 28 and 32% increase in biological yield at BARI Chakwal, while 20 and 30% at Farmer's field Talagang. Similarly, yield increase recorded with S application (15 & 30 kg ha^{-1}) was 14 and 17% for BARI, Chakwal and 8 and 11% for farmer's field Talagang.

Zinc uptake. At BARI Chakwal, different S and P rates as well as their interaction had significant effect on Zn uptake in straw (Table V). Phosphorus (40 & 80 kg ha^{-1}) and sulfur (15 & 30 kg ha^{-1}) application resulted in increase in Zn uptake by 20 and 16% and by 25 and 23%, respectively. Difference between P_1 (40 kg P_2O_5 ha^{-1}) and P_2 (80 kg P_2O_5 ha^{-1}) and S_1 (15 kg S ha^{-1}) and S_2 (30 kg S ha^{-1}) was non significant. Among S and P interactions, highest uptake (25.99 g ha^{-1}) was recorded in P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}) followed by P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}) and P_1S_1 (40 kg P_2O_5 & 15 kg S ha^{-1}), which were significantly lower than former but were at par with each other. Minimum Zn uptake (16.49 g ha^{-1}) was recorded for P_0S_0.

At farmer's field Talagang, different S and P rates had significant effect on Zn uptake but P × S interaction was non significant (Table V). Lower level of P application (40 kg ha^{-1}) resulted in increase in Zn uptake by 25%, while 80 kg P_2O_5 ha^{-1} had non significant effect on Zn uptake as compared with that of control. sulfur application (15 & 30 kg/ha) resulted in increase in Zn uptake by 4 and 9% over control.

Sulfur application had significant effect on Zn uptake in grain at both locations (Table VI). Effect of P application as well as P by S interaction on Zn uptake in grain was non significant. Sulfur application resulted in 17 and 16% increase in Zn uptake over control at BARI Chakwal and by 11 and 18% at farmer's field Talagang. Difference between lower (15 kg ha^{-1}) and higher level (30 kg ha^{-1}) of S application was non significant.

Table I. Physical and chemical properties of soils of experimental sites

Soil characteristic	BARI Chakwal	Farmer's field Talagang
Texture	Sandy loam	Loamy sand
pH	7.6	7.7
Organic C (g kg^{-1})	3.7	1.8
Phosphorus (AB-DTPA extractable, mg kg^{-1})	2.9	1.4
Sulphate- Sulphur ($CaCl_2$ extractable, mg kg^{-1})	6.4	7.5
Zinc(AB-DTPA extractable, mg kg^{-1})	0.75	1.30
Copper (AB-DTPA extractable, mg kg^{-1})	1.21	0.92
Fe (AB-DTPA extractable, mg kg^{-1})	7.82	5.63
Mn (AB-DTPA extractable, mg kg^{-1})	2.98	2.10

Table II. Details of combinations of phosphorus and sulphur applied in different treatments

Treatments*	Fertilizer rates (Kg ha^{-1})	
	P	S
T1 (P_0S_0)	0	0
T2(P_0L_1)	0	15
T3 (P_0S_2)	0	30
T4 (P_1S_0)	40	0
T5(P_1S_1)	40	15
T6 (P_1S_2)	40	30
T7 (P_2S_0)	80	0
T8 (P_2S_1)	80	15
T9 (P_2S_2)	80	30

*P_0, P_1 and P_2 stand for application of 0, 40 and 80 kg P_2O_5 ha^{-1} and S_0, S_1 and S_2 for 0, 15 and 30 kg S ha^{-1}

Table III. Effect of integrated use of P and S on seed yield at two locations (kg ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	926 h	1178 e	1220 d	1108 c	1562	1880	2173	1872 b
S1	988 g	1339 c	1385 b	1237 b	1660	2120	2380	2053 a
S2	1025 f	1422 a	1353 bc	1267 a	1952	2290	2293	2178 a
Mean	980 b	1313 a	1319 a		1725 c	2097 b	2282 a	

Table VI. Effect of integrated application of P and S on biological yield at two locations (kg ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	3120	3633	3816	3523 b	3493	4008	4621	4041 c
S1	3185	4198	4614	3999 a	3645	4486	4919	4350 b
S2	3422	4586	4406	4138 a	3913	4721	4829	4488 a
Mean	3242 b	4139 a	4279 a		3684 b	4405 a	4790 a	

Table V. Effect of integrated application of P and S on Zn uptake in straw at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	16.49 d	17.85 d	18.69 cd	17.68b	14.56	18.34	15.38	16.09 b
S1	19.79 d	23.00 b	23.45 b	22.08a	15.28	19.26	15.73	16.76 b
S2	18.19 d	25.99 a	21.15 bc	21.78a	16.65	20.41	15.68	17.58 a
Mean	18.16 b	22.28 a	21.10 a		15.50 b	19.34a	15.60b	

Copper uptake. Some what different results were recorded for Cu uptake in straw at two locations (Table VII). At BARI Chakwal S application had significant effect on Cu uptake increasing it by 30 and 59% over control. Effect of sole P as well as combined application of P and S had non significant effect on Cu uptake.

Table VI. Effect of integrated application of P and S on Zn uptake in grain at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	16.49	22.71	17.91	19.04 c	30.77	33.81	38.01	34.20b
S1	18.23	25.96	22.57	22.25 b	32.99	39.23	41.66	37.96a
S2	21.13	28.48	22.11	23.91 a	38.55	42.73	39.81	40.36a
Mean	18.62	25.72	20.86		34.10	38.59	39.83	

Table VII. Effect of integrated application of P and S on Cu uptake in straw at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	7.22	9.83	9.66	8.90 c	12.59bc	9.20 d	13.50 abc	11.76
S1	7.40	12.64	14.73	11.59 b	12.99abc	11.76 c	15.13 ab	13.29
S2	9.32	18.53	14.72	14.19 a	8.19d	15.37 a	13.40 abc	12.32
Mean	7.98	13.67	13.04		11.26	12.11	14.01	

Table VIII. Effect of integrated application of P and S on Cu uptake in grain at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	6.18 e	8.46d	10.76c	8.47c	12.20e	13.93cde	16.25bc	14.13
S1	6.68 e	10.44c	12.30a	9.81b	12.77de	16.64abc	18.36ab	15.92
S2	8.67 d	11.19bc	11.83ab	10.56a	16.25bc	19.19a	15.05cd	16.83
Mean	7.18 c	10.03b	11.63a		13.74	16.59	16.55	

Table XI. Effect of integrated application of P and S on Fe uptake in straw at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	63 d	75 bcd	85 bcd	74 c	59 e	66 de	63 de	62 c
S1	90 bc	94 b	145 a	110 b	63 de	74 cd	87 b	74 b
S2	67 cd	159 a	153 a	126 a	63 de	84 bc	111 a	86 a
Mean	74 b	109 a	128 a		62 c	74 b	87 a	

Table X. Effect of integrated application of P and S on Fe uptake in grain at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	24.12	28.4	21.94	24.82 c	22.78 e	38.11 cd	48.90 a	36.60
S1	25.21	36.79	30.54	30.85 b	27.85 e	42.22 bc	46.47 ab	38.85
S2	29.92	37.92	32.15	33.33 a	33.97 d	43.94 ab	44.11 ab	40.67
Mean	26.42	34.37	28.21		28.20 b	41.42 a	46.49 a	

Table XI. Effect of integrated application of P and S on Mn uptake in straw at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	24.81	27.73	27.94	26.83 b	22.60	25.98	31.09	26.56
S1	31.54	33.84	37.06	34.15 a	24.39	28.07	32.59	28.35
S2	33.90	44.95	35.83	38.23 a	23.02	28.12	30.45	27.20
Mean	30.08	35.51	33.61		23.34 c	27.39 b	31.38 a	

At farmer' field Talagang, individual application of P and S had non significant effect but their integrated application had significant effect on Cu uptake. Maximum uptake (15.37 g ha^{-1}) was recorded in P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}), which was at par with P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}), P_2S_0 (80 kg P_2O_5 & 0 kg S ha^{-1}) and P_2S_2 (80 kg P_2O_5 & 30 kg S ha^{-1}). At lower rate (40 kg ha^{-1}) of P application, S application resulted in increase in Cu uptake but at higher rate of P application (80 kg ha^{-1}), difference in Cu uptake was non significant.

Effect of individual application of P and S as well as their interaction were significant for Cu uptake in grain at BARI Chakwal (Table VIII). Increase in Cu uptake due to P (40 & 80 kg ha^{-1}) and S (15 & 30 kg ha^{-1}) application was 40 and 62 and 16 and 25%, respectively. Uptake at higher levels of P (80 kg ha^{-1}) and S (30 kg ha^{-1}) was significantly higher than lower levels of nutrient application. Highest Cu uptake (12.30 g ha^{-1}) was recorded in P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}) followed by P_2S_2 (80 kg P_2O_5 & 30 kg S ha^{-1}), which was at par with P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}). Minimum uptake was recorded in P_0S_0.

At farmer's field Talagang, application of P and S had non significant effect but their interaction had significant effect on Cu uptake. Maximum uptake (19.19 g ha^{-1}) was observed in plot having treatment P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}), which was at par with that of P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}) and P_1S_1 (40 kg P_2O_5 & 15 kg S ha^{-1}). There was significant reduction in Cu uptake (15.05 g ha^{-1}) at higher rate of P (80 kg ha^{-1}) and S (30 kg ha^{-1}) application. Minimum Cu uptake (12.20 g ha^{-1}) was recorded in P_0S_0.

Iron uptake. Almost same trend for Fe uptake in straw was observed at both locations (Table IX). There was significant effect of P and S application at both locations. At BARI Chakwal, P (40 & 80 kg ha^{-1}) and S (15 & 30 kg ha^{-1}) application resulted in 49 and 74% and 48 and 70% increase in yield over control, respectively. Difference between lower (40 kg ha^{-1}) and higher level (80 kg ha^{-1}) of P was non significant but was significant for S (15 & 30 kg ha^{-1}).

At farmer's field Talagang, P (40 & 80 kg ha^{-1}) and S (15 & 30 kg ha^{-1}) application resulted in 21 and 41 and 19 and 38% increase in yield over control, respectively. Difference between higher and lower level of P and S was significant. The P × S interaction was also significant with the highest Fe uptake (111 g ha^{-1}) observed in P_2S_2 (80 kg P_2O_5 & 30 kg S ha^{-1}), which was significantly higher than mutually non significant treatments P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}) and P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}). Minimum Fe uptake (59 g ha^{-1}) was recorded in P_0S_0.

Some what different results were recorded for Fe uptake in grain at both locations (Table X). At BARI Chakwal, S application had significant effect on Fe uptake increasing it by 24 and 34%, while effect of P was non significant. There was significant difference between lower (15 kg ha^{-1}) and higher (30 kg ha^{-1}) level of S application.

At farmer's field Talagang, S had non significant effect but effect of P and as well as P by S interaction was significant on Fe uptake in grain. An increase of 47 and 65% was observed in Fe uptake over control due to P application (40 & 80 kg ha^{-1}). Difference between higher (80 kg ha^{-1}) and lower level (40 kg ha^{-1}) was non significant. Maximum uptake (48.90 g ha^{-1}) was recorded in P_0S_0 (control), which was at par with P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}), P_2S_2 (80 kg P_2O_5 & 30 kg S ha^{-1}) and P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}). Minimum uptake was recorded in P_0S_0.

Table XII. Effect of integrated application of P and S on Mn uptake in grain at two locations (g ha^{-1})

	BARI Chakwal				Farmer's field, Talagang			
	P0	P1	P2	Mean	P0	P1	P2	Mean
S0	24.1 de	28.4c	23.4e	25.3c	48.4ef	44.9 f	55.6bcde	49.68b
S1	25.8 d	39.5a	30.6bc	32.0b	50.1def	56.3bcd	63.7a	56.75a
S2	29.9 bc	41.2a	32.2b	34.4a	57.8abc	61.3ab	51.9cdef	57.02a
Mean	26.63	36.40	28.72		52.13	54.21	57.11	

Table XIII. Regression Analysis

Characteristics	BARI Chakwal		Farmer's field, Talagang	
	Regression equation	R^2	Regression equation	R^2
Seed Yield	955+4.25 P+5.30 S	75	1603+6.97 P+10.2 S	73
Biological Yield	3061+13 P+20.5 S	65	3516+13.8 P+14.9 S	72
Zn uptake in Straw	16.2+0.049 P+0.14 S	42	16+0.0013 P+0.049 S	8
Zn uptake in Grain	18.2+0.028 P+0.162 S	25	31.6+0.071 P+0.21 S	30
Cu uptake in Straw	6.39+0.0632 P+0.176 S	48	10.8+0.034 P+0.0186 S	16
Cu uptake in Grain	6.34+0.055 P+0.07 S	88	13.2+0.0477 P+0.056 S	26
Fe uptake in Straw	50.4+0.677 P+1.74 S	60	50+0.32 P+0.78 S	63
Fe uptake in Grain	24.5+0.022 P+0.284 S	37	28+0.23 P+0.14 S	62
Mn uptake in Straw	25.6+0.044 P+0.38 S	33	23+0.11 P+0.02 S	76
Mn uptake in Grain	25+0.0262 P+0.305 S	34	48.3+0.0622 P+0.245 S	18

Manganese uptake. Sulfur application (15 & 30 kg ha^{-1}) had significant effect on Mn uptake in grain at BARI Chakwal increasing it by 27 and 42% (Table IX). Difference between S_1 and S_2 was non significant. Individual application of P as well as combined application of P and S had non significant effect on Mn uptake in straw.

There was significant effect of P application on Mn uptake but individual as well as integrated application of P and S had non significant effect on Mn uptake at farmer's field Talagang. Phosphorus application (40 & 80 kg ha^{-1}) resulted in 17 and 34% increase in Mn uptake. Difference between P_1 and P_2 was significant.

Almost similar trend was observed regarding Mn uptake in grain at two locations (Table XII). S application (15 & 30 kg ha^{-1}) resulted in 26 and 36% increase in Mn uptake at BARI Chakwal and 14 and 15% increase at farmer's field Talagang. Difference between S_1 and S_2 was significant at BARI Chakwal, while non significant at farmer's field Talagang. Maximum uptake (41.2 g ha^{-1}) was recorded in plot with treatment application P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}), which was at par with P_1S_1 (40 kg P_2O_5 & 15 kg S ha^{-1}). Higher rate of P (80 kg ha^{-1}) resulted in significant reduction in Mn uptake as compared to lower one (40 kg ha^{-1}). Minimum uptake (23.4) was recorded in P_2S_0 (80 kg P_2O_5 & 0 kg S ha^{-1}). At farmer's field Talagang, maximum uptake (63.7 g ha^{-1}) was recorded in P_2S_1 (80 kg P_2O_5 & 15 kg S ha^{-1}), which was at par with P_1S_2 (40 kg P_2O_5 & 30 kg S ha^{-1}) and P_0S_2 (0 kg P_2O_5 & 30 kg S ha^{-1}). Combined application of higher level of P (80 kg ha^{-1}) and S (30 kg ha^{-1}) resulted in significant decrease (51.9 g ha^{-1}) in Mn uptake. Minimum Mn uptake (44.9 g ha^{-1}) was recorded in P_1S_0 (40 kg P_2O_5 & 0 kg S ha^{-1}).

DISCUSSION

Sulfur and phosphorus interaction was synergistic at BARI Chakwal. At farmer's field Talagang interaction between two nutrients was synergistic at low rate of P application (40 kg ha^{-1}) and antagonistic at higher rate (80 kg ha^{-1}). Antagonism between P and S at farmer's field Talagang may be due to coarse texture of soil resulting in more leaching losses of sulfur than at BARI Chakwal. Randhawa and Arora (2000) observed a highly significant positive interaction between P and S in terms of P uptake leading to higher seed yield of wheat at low rate of S application. Higher rates of S application caused antagonistic effect. Sulphate adsorption is completely stopped by the presence of two- thirds of equivalent amount of phosphate compared to sulphate (Abdin *et al.*, 2003). Higher response to the application of both nutrients was noticed at farmer's field Talagang as compared to Chakwal (Table XIII). This may be due to favorable climatic conditions especially higher moisture availability at time of sowing and low initial fertility status of experimental site (Table I). Higher rainfall (353 mm) was recorded recorded for Talagang as compared to Chakwal (234 mm) for period from July to September 2006 resulting in better germination and rapid early crop growth. Higher response to application of S than P as depicted in regression analysis (Table XIII) may be due to application of lower rates of S.

Growth is a function of many controllable and un-controllable factors and balanced nutrition has key role among these factors. Sulfur availability may influence photosynthetic rate since ferredoxin and acetyl-CoA contain S and play a significant role in the reduction of CO_2 and production of organic compounds (Von Uexkull, 1986). Several studies have shown the positive effect of P and S application on root growth and morphology (Hilal *et al.,* 1990a; Bagayoko *et al.,* 2000). Due to acidifying effect of S oxidation, the availability of other nutrients like P, Zn, Cu, Fe and Mn is also influenced (Hilal *et al.,* 1990b) Application of P and S resulted in increased uptake of these nutrients by plant, which may be due to their increased availability in soil. Higher rate of P application (80 kg ha^{-1}) resulted in decrease in Zn uptake in both straw and grain. This may be either due to dilution effect when rate of plant growth exceeded that of Zn uptake or due to reduction in translocation of Zn from roots to leaves (Tandon, 2001). The hypothesis that P application resulted in the formation of insoluble zinc phosphate is not true and many workers have shown that P application has no effect on available Zn contents in soil (Tandon, 2001). Increase in Zn uptake in response to S application has been reported earlier (Sharma *et al.,* 1990; Babhulkar *et al.*, 2000). Increased Zn uptake may be due to increased root surface area resulting from better growth due to S supply as both S and Zn are known to increase root growth. Studies show that Zn and S interaction occurs at both absorption sites and within plants (Babhulkar *et al*., 2000). Some reports however show antagonistic relationship between S and Zn (Kumar *et al.,* 1997).

Increase in Cu uptake with P application may be due to increased root growth, which resulted in better exploration of soil volume. These results are not in line with previous findings of Tandon (2001) who observed an antagonistic effect of Cu and P in rice when one of the nutrient was applied in large quantity. Higher rate of P application was found to have no influence on Cu concentration in red kidney beans, tomato or sweet corn. This difference between genera and species of plants might be attributed to the genetic composition of plant species (Tandon, 2001). Many workers have reported reduced uptake of Cu due to high rate of P application (Havlin, 2007). Phosphorus application may result in the formation of copper phosphate, which is not readily available to plants.

Sulfur application resulted in increase in Fe uptake, as was also recorded by Malewar and Ismail (1997). They observed that application of 80 mg S kg^{-1} increased Fe availability by 49%. They concluded that there exists a close relationship between Fe and S metabolism in plants.

Sulfur application had significant effect on Mn uptake. Among micronutrients, interaction between S and Mn is least studied. Exact mechanism responsible for increased Mn uptake is not known. Havlin *et al.* (2007) reported that application of acid (NH_4^+) forming fertilizer may increase availability of Mn. Phosphorus application had significant effect on Mn uptake. Possible mechanism responsible for less uptake of Mn at higher nutrient application rates may be that other cations also compete with Mn for transport across membranes. High concentration of Ca^{2+} and Mg^{2+} absorbed to apoplasmic (root) cell walls, especially in high pH soils can reduce Mn^{2+} adsorption to cell walls and eventual transport in to cell (Havlin *et al.,* 2007).

CONCLUSION

Type of interaction between P and S depends on initial soil fertility status, levels of nutrients applied, test crop and climatic conditions of the region during crop growth period. Interaction between P and S was synergistic at BARI Chakwal but antagonistic at farmer's filed, Talagang, when higher P was applied in combination with higher rate of S. Nutrient combinations of 40 kg P_2O_5 ha^{-1} and 30 kg S ha^{-1} or 80 kg P_2O_5 ha^{-1} and 15 kg S ha^{-1} resulted in maximum yield of crop. This will not only result in increased fertilizer use efficiency and saving of precious and costly inputs but will also minimize the threats of soil and water pollution.

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