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## RESPONSE OF SOIL P FRACTIONS AND ITS UPTAKE BY WHEAT IN DIFFERENT P CONTAINING SOILS ON APPLICATION OF DIFFERENT LEVELS OF P AND Zn

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### ABSTRACT

Phosphorus (P) and zinc (Zn) are vital nutrients for normal plant growth, but their deficiencies have become a major limitation to crop productivity. Therefore, optimizing their levels through balanced fertilizer application is crucial. However, under certain conditions, P and Zn can act antagonistically. To gain deeper insight into this interaction, a study was carried out in sandy and sandy loam soils with different P levels to examine the interactive effect of P and Zn on native pools of P and uptake of P by wheat. The study aimed to evaluate the interactive effects of P and Zn on both fractions of P and the uptake of P by wheat. Results revealed that increasing P levels significantly enhanced the concentration of various P fractions in both types of soil, with highest concentration observed at higher P dose. Conversely, the influence of Zn levels and the interaction between P and Zn on P fractions was observed non-significant. The concentration of P fractions was higher in soil with high P content compared to those with low P content. Calcium-bound P (Ca-P) was most prevalent form and the Saloid-bound P was the least abundant. The order of abundance of P fractions: Ca-P > Org-P > Al-P > Fe-P > Red-P > Saloid-P, remained consistent across both types of soils. Also, P uptake in both grain and straw of wheat increased with increasing level of P and Zn in both the soil but their interactive effect was found non-significant in high P status soil. As a result, the study helps to maximise P and Zn fertilisation levels in both high and low P soils. Consequently, the study aids in optimizing P and Zn fertilization strategies across soils with varying P levels. It underscores the need for precise management of phosphorus applications, particularly in soils with differing initial P concentrations, to prevent adverse interactions with zinc and enhance nutrient absorption in wheat crops.

**Keywords :** Wheat, P uptake, low P status soil, high P status soil, Zn fractions, P fractions.

### Introduction

Plant nutrients availability in soils has always been a factor determining crop growth and development. The availability of plant nutrients becomes limited either due to the indigenous low fertility status of soils or the nature of parent material along with the antagonistic chemical interactions. Phosphorus (P) is an essential macronutrient, while zinc (Zn) is a vital micronutrient for crop growth and development in any agricultural production system (Nadeem *et al.*, 2024). Deficiency of either nutrient can severely restrict crop growth, yield, and grain quality, particularly in cereals such as wheat (*Triticum*

*aestivum* L.), which is the most widely grown staple crop across the world. Given the centrality of wheat in global diets, enhancing its nutrient uptake efficiency through balanced fertilization strategies has become an urgent research priority. The interaction between P and Zn in soils adds further complexity to nutrient management. High phosphorus application has often been reported to induce zinc deficiency in plants, a phenomenon widely described as 'P-induced Zn deficiency' (Dhaliwal *et al.*, 2023). This occurs due to dilution effects, metabolic imbalances, or the precipitation of Zn into unavailable forms under conditions of excess P. Conversely, Zn-induced P

deficiency is rare because P is generally applied at much higher rates than Zn in agricultural systems. While the antagonistic interaction between P and Zn is well recognized, its intensity and significance are highly variable and strongly dependent on soil properties, P status, and fertilizer management practices. In low P status soils, Zn application may help enhance P use efficiency, while in high P soils, the P × Zn interaction may become negligible. The presence of available P in excess leads to Zn deficiency in plants growing on Zn deficient soils (Dhaliwal and Mandal, 2019). The interactions between P and Zn depend upon the concentrations of P and Zn in soil as well as plant species. The availability of P in marginal to normal amounts in soil has shown synergetic or no interaction with each other. On the contrary, the excessive amount of P antagonizes other nutrients particularly Zn and causes its deficiency (Soltanghei *et al.*, 2013). A number of studies have shown that inappropriate applications of Zn and P have aggravated their respective deficiencies in soil. However, the information regarding the optimum level of P and Zn deficiency in different soils for higher crop productivity, Zn and P uptake by crops are scanty. Thus, a context-specific understanding of these interactions is vital for improving both crop nutrition and soil fertility management.

Also, the global P fertilizer use in agriculture has increased rapidly during the past five decades to feed large population. Application of P fertilizers increases the available levels of P and crop production (Jiang *et al.*, 2018). Although the application of P is required to achieve high wheat yields (Cordell *et al.*, 2009, MacDonald *et al.*, 2011, Gemenet *et al.*, 2015), excessive P fertilization can lead to surplus levels of P in croplands (MacDonald *et al.*, 2011) and then to reduced environmental quality and food security (Cordell *et al.*, 2009). The application of P to soil yields only 10–20% output as compared to its input to soil for crop utilization (Sattari *et al.*, 2012). Excessive P application can alter soil P availability and limit plant growth by making the soil compact and fixing P into the soil in different organic and inorganic forms. However, it remains uncertain whether these changes happen after limited fertilization or an excessive rate applied under the wheat cropping system (Mahmood *et al.*, 2020). As an element, phosphorus is highly reactive. Large quantity applied to soil influence the deposition and affects P cycling (Elser *et al.*, 2012). The response to different soil conditions and P fertilization input is a common study topic. However, significant uncertainty remains regarding the P found in different forms adsorbed on the soil surface with different elements [*i.e.*, iron (Fe), aluminum (Al) and

calcium (Ca)], which differ in their bioavailability, mobility and behavior in the soil, depending on pH, parent material and fertilization background (Mehmood *et al.*, 2015). Consequently, it is important to assess the effects of P application on P limitation with different fertilizer rates and different mechanisms. It is also essential to study the effects of different rates of P inputs on P fractions and their relationship with crop yield and availability. Phosphorus availability in soil is highly dependent on P fractions, which affect its primary production (Williams *et al.*, 2013). High rates of P fertilization result in rapid formation of non-labile P forms (Malik *et al.*, 2012). Excess phosphorus (P) fertilizer application leads to P accumulation in soil over time, necessitating an optimal balance of P and Zn for sustainable wheat growth and yield. Despite extensive studies on P fertilization and its impacts on crop yields, relatively limited information is available on how phosphorus fractions are influenced under combined application of P and Zn in soils differing in their inherent P status. Most past research has focused either on total P uptake or on Zn nutrition, but studies integrating both aspects while simultaneously examining soil P fractionation remain scarce. This is a critical knowledge gap, because the distribution of P fractions determines not only the immediate nutrient availability but also the long-term sustainability of fertilizer use. Moreover, understanding how P × Zn interactions affect these fractions could provide valuable insights into nutrient cycling and improve management recommendations for sustainable wheat production systems. Therefore, the present study was undertaken to evaluate the impact of different levels of P and Zn on the transformation of soil phosphorus fractions and their uptake by wheat in soils having varying P levels.

## Material and Methods

### Soil collection

To conduct this experiment, two soils of different available P status [on the basis of 0.5M sodium bicarbonate (NaHCO<sub>3</sub>) extractable -P] were collected from surface layer (0-15 cm) from the farmer's fields from two different locations of Haryana, *viz.* Sadalpur (Hisar) and Saniyana (Fatehabad) and brought to screen house of the Department of Soil Science, CCS HAU, Hisar during *Rabi* season of 2018-19. The soil collected from village Saniyana was high in Olsen's P (25 kg P ha<sup>-1</sup>), whereas, that collected from village Sadalpur was low in available P (8 kg P ha<sup>-1</sup>) content. The application of phosphorus fertilizer is being practiced by the farmers in both the soils. Detailed physicochemical characterization of the soils used in this study was done by using their standard

methodology. The soil with low available P status exhibited a pH of 7.4, an electrical conductivity (EC) of 0.12 dS m<sup>-1</sup>, an oxidizable organic carbon (OC) content of 0.15% and a cation exchange capacity (CEC) of 4.46 cmol (p+) kg<sup>-1</sup>, with sandy texture. It contained available nitrogen (N), phosphorus (P) and potassium (K) at levels of 28, 8 and 112 kg ha<sup>-1</sup>, respectively. The DTPA extractable micronutrients were measured at 0.30 mg kg<sup>-1</sup> for zinc (Zn), 1.94 mg kg<sup>-1</sup> for copper (Cu), 2.11 mg kg<sup>-1</sup> for iron (Fe) and 2.48 mg kg<sup>-1</sup> for manganese (Mn). Conversely, the soil with high Olsen's P status had a pH of 7.1, an EC of 1.0 dS m<sup>-1</sup>, an oxidizable OC of 0.62% and a CEC of 9.28 cmol (p+) kg<sup>-1</sup> with texture sandy loam. The levels of available N, P and K were 182, 25 and 430 kg ha<sup>-1</sup>, respectively. The DTPA extractable micronutrients in this soil were 0.72 mg kg<sup>-1</sup> for Zn, 3.08 mg kg<sup>-1</sup> for Cu, 18.74 mg kg<sup>-1</sup> for Fe, and 10.26 mg kg<sup>-1</sup> for Mn.

### Pot experiment

The two soils were air dried, ground and passed through stainless sieve with aperture 2mm. The experiment was conducted in the screen house in plastic pots containing four kg of soil with five levels of phosphorus (0, 30, 60, 120 and 180 mg kg<sup>-1</sup> soil) and four levels of zinc (0, 2.5, 5 and 10 mg kg<sup>-1</sup>). Phosphorus was applied to the soils as KH<sub>2</sub>PO<sub>4</sub> and zinc as ZnSO<sub>4</sub>·7H<sub>2</sub>O. Treatments of P and Zn were applied at the time of sowing along with recommended basal dose of nitrogen (through urea). All the treatments were laid out in completely randomized design (CRD) and replicated thrice. The soil of the pots was moistened with water and mixed thoroughly. Ten seeds of wheat (variety WH 1105) were sown during second fortnight of november in each pot and were thinned to four seedlings per pot after emergence. The plants were allowed to grow up to maturity. After harvesting the crop, the soil samples were collected from each pot and brought to the laboratory. The soil samples of two soils were air dried, crushed and sieved (2mm) and analyzed for various phosphorus fractions.

### Sequential soil P extraction

The processed soil samples taken from each pot after the harvesting the crop were used for phosphorus fractions (saloid-P, aluminium-P, iron-P, reductant soluble-P, calcium-P and organic-P). A sequential fractionation for soil inorganic phosphorus was performed by following a method outlined by Chang and Jackson (1957) and modified by Peterson and Corey (1966).

### Plant sampling and analysis

The grain and straw samples of wheat were collected from each pot at crop maturity and dried at room temperature then ground and digested in a diacid mixture of nitric acid (HNO<sub>3</sub>) and perchloric acid in ratio 4:1 ratio. The digested mixture was then filtered and final volume was made 50 ml and stored for further analysis of P. The digests were analyzed for Zn on atomic absorption spectrophotometer (AAS).

Uptake of P was computed from the data of P (mg kg<sup>-1</sup>) concentration and grain and straw yield (g pot<sup>-1</sup>) by using the following formula:

**Nutrient uptake** = Nutrient concentration in grain or straw (% or mg kg<sup>-1</sup>) x grain or straw yield (g pot<sup>-1</sup>)

## Results

### Effect of graded levels of P and Zn on P uptake

The data presented in Table 1 indicate that the mean P uptake by both grain and straw in low P status soil increased with higher levels of P and Zn application. In response to P application, the highest P uptake, reaching 2.36 mg pot<sup>-1</sup> in grain and 0.28 mg pot<sup>-1</sup> in straw, was observed at highest P level (180 mg P kg<sup>-1</sup>). Similarly, with Zn application, the maximum P uptake by grain (2.23 mg pot<sup>-1</sup>) and straw (0.24 mg pot<sup>-1</sup>) was noted at 10 mg Zn kg<sup>-1</sup> level. The interactive effect of P and Zn was also significant on P uptake by both grain and straw. However, the maximum P uptake by grain (2.44 mg pot<sup>-1</sup>) was achieved with the application of P 180 mg kg<sup>-1</sup> along with Zn 10 mg kg<sup>-1</sup>. Conversely, for straw, the highest P uptake (0.29 mg pot<sup>-1</sup>) was observed at a P level of 180 mg kg<sup>-1</sup>.

Each successive level of P and Zn exhibited an additive effect on P uptake by both grain and straw in high P status soil (Table 2). Regarding P treatment, the highest P uptake by grain (2.58 mg pot<sup>-1</sup>) was observed at a P level of 180 mg kg<sup>-1</sup>, while for straw, the highest P uptake (0.28 mg pot<sup>-1</sup>) was recorded at P level of 60 and 180 mg kg<sup>-1</sup>. In the case of Zn treatments, the maximum mean P uptake by both grain (2.70 mg pot<sup>-1</sup>) and straw (0.30 mg pot<sup>-1</sup>) was observed at the highest Zn dose (10 mg Zn kg<sup>-1</sup>). However, the interaction effect of P and Zn on P uptake was found to be non-significant.

**Table 1:** Effect of P and Zn on the phosphorus uptake (mg pot<sup>-1</sup>) by wheat grain and straw in low Olsen's P status soil

P levels (mg kg <sup>-1</sup> )	Zn levels (mg kg <sup>-1</sup> )				Mean
	0	2.5	5	10	
<b>Grain</b>					
0	0.11	1.17	1.50	1.88	1.16
30	1.69	1.72	1.90	2.20	1.88
60	1.83	1.99	2.33	2.28	2.11

<b>120</b>	1.98	2.21	2.34	2.36	2.22
<b>180</b>	2.30	2.35	2.34	2.44	2.36
<b>Mean</b>	1.58	1.89	2.08	2.23	
<b>CD (p- 0.05)</b>	P-0.13		Zn-0.12	PxZn-0.27	
<b>Straw</b>					
<b>0</b>	0.01	0.14	0.16	0.19	0.12
<b>30</b>	0.20	0.22	0.22	0.23	0.22
<b>60</b>	0.22	0.26	0.28	0.26	0.26
<b>120</b>	0.24	0.27	0.27	0.27	0.26
<b>180</b>	0.29	0.28	0.26	0.27	0.28
<b>Mean</b>	0.19	0.23	0.24	0.24	
<b>CD (p- 0.05)</b>	P- 0.02		Zn-0.02	PxZn-0.03	

**Table 2:** Effect of P and Zn on the phosphorus uptake (mg pot<sup>-1</sup>) by wheat grain and straw in high Olsen’s P status soil

P level (mg kg <sup>-1</sup> )	Zn level (mg kg <sup>-1</sup> )				Mean
	0	2.5	5	10	
<b>Grain</b>					
<b>0</b>	1.35	1.84	2.11	2.54	1.96
<b>30</b>	1.77	1.86	2.25	2.55	2.11
<b>60</b>	1.84	2.12	2.48	2.72	2.29
<b>120</b>	2.02	2.34	2.56	2.80	2.43
<b>180</b>	2.46	2.41	2.56	2.88	2.58
<b>Mean</b>	1.89	2.11	2.39	2.70	
<b>CD (p- 0.05)</b>	P-0.14		Zn-0.13	PxZn-NS	
<b>Straw</b>					
<b>0</b>	0.16	0.22	0.24	0.27	0.22
<b>30</b>	0.20	0.23	0.25	0.29	0.24
<b>60</b>	0.23	0.27	0.30	0.33	0.28
<b>120</b>	0.23	0.26	0.29	0.31	0.27
<b>180</b>	0.26	0.27	0.28	0.32	0.28
<b>Mean</b>	0.22	0.25	0.27	0.30	
<b>CD (p- 0.05)</b>	P-0.02		Zn-0.02	PxZn-NS	

**Phosphorus fractions in low and high Olsen’s P status soils**

**Saloid-P**

The data in Table 3 demonstrate a notable impact of phosphorus (P) application on saloid-P content in both low and high P status soils. Increasing P levels from 0 to 180 mg P kg<sup>-1</sup> resulted in a significant rise in saloid-P content, reaching 17.75 mg kg<sup>-1</sup> in low P status soil and 19.66 mg kg<sup>-1</sup> in high P status soil. However, the addition of zinc (Zn) at various levels, either alone or in combination of P, did not show a significant effect on saloid-P content. Nonetheless, it is noteworthy that at each increment of applied P, the average saloid-P content was consistently higher in high P status soil as compared to low P status soil.

**Aluminium-P (Al-P)**

The data provided in Table 4 illustrate a substantial increase in mean Al-P content with the escalation of P levels from 0 to 180 mg kg<sup>-1</sup>. In low P status soil, the mean Al-P content rose significantly

from 25.59 to 74.42 mg kg<sup>-1</sup>, while in high P status soil, it increased from 72.31 to 137.33 mg kg<sup>-1</sup>. The highest mean Al-P content in both low P status soil (74.42 mg kg<sup>-1</sup>) and high P status soil (137.33 mg kg<sup>-1</sup>) was observed at the application of P 180 mg kg<sup>-1</sup>. The application of various levels of Zn, whether alone or combined with different P levels, did not exert a significant influence on Al-bound P content in either soil type. Notably, the mean Al-P content was consistently higher in high P status soil as compared to low P status soil.

**Table 3:** Effect of different levels of P and Zn on saloid-P content (mg kg<sup>-1</sup>) in low and high Olsen’s P status soils

P levels (mg kg <sup>-1</sup> )	Zn levels (mg kg <sup>-1</sup> )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
<b>0</b>	2.92	3.00	2.82	2.76	2.88
<b>30</b>	5.08	5.20	5.00	5.10	5.10
<b>60</b>	6.10	6.25	6.34	6.42	6.28
<b>120</b>	14.00	13.90	13.40	13.20	13.63
<b>180</b>	18.04	17.64	18.00	17.32	17.75
<b>Mean</b>	9.23	9.20	9.11	8.96	
<b>CD (p- 0.05)</b>	P- 0.72		Zn- NS	PxZn- NS	
<b>High P status soil</b>					
<b>0</b>	4.17	4.25	4.07	4.43	4.23
<b>30</b>	6.75	6.90	6.71	6.59	6.74
<b>60</b>	7.60	7.75	7.84	8.01	7.80
<b>120</b>	15.60	15.39	14.83	15.02	15.21
<b>180</b>	20.30	19.50	19.76	19.08	19.66
<b>Mean</b>	10.89	10.76	10.64	10.63	
<b>CD (p- 0.05)</b>	P- 0.77		Zn- NS	PxZn- NS	

**Table 4:** Effect of different levels P and Zn on Al-P content (mg kg<sup>-1</sup>) in low and high Olsen’s P status soils

P levels (mg kg <sup>-1</sup> )	Zn levels (mg kg <sup>-1</sup> )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
<b>0</b>	25.20	26.54	25.62	24.98	25.59
<b>30</b>	31.35	32.60	32.90	33.25	32.53
<b>60</b>	36.58	37.20	38.20	38.50	37.62
<b>120</b>	60.50	58.52	57.59	54.54	57.79
<b>180</b>	79.24	74.65	72.54	71.25	74.42
<b>Mean</b>	46.57	45.90	45.37	44.51	
<b>CD (p- 0.05)</b>	P- 2.58		Zn- NS	PxZn- NS	
<b>High P status soil</b>					
<b>0</b>	70.40	72.57	70.34	75.92	72.31
<b>30</b>	107.86	110.58	106.77	107.19	108.10
<b>60</b>	114.46	116.28	112.70	110.48	113.48
<b>120</b>	125.30	134.20	118.24	124.63	125.59
<b>180</b>	142.64	138.26	136.34	132.10	137.33
<b>Mean</b>	112.13	114.38	108.88	110.06	
<b>CD (p- 0.05)</b>	P- 6.30		Zn- NS	PxZn- NS	

### Iron-P (Fe-P)

It is evident from the Table 5 that the average Fe-P content increased from 35.24 to 82.42 mg kg<sup>-1</sup> in low P status soil and from 39.81 to 95.67 mg kg<sup>-1</sup> in high P status soil with each incremental level of P application as compared to their respective control (23.52 and 39.81 mg kg<sup>-1</sup>). The highest mean Fe-P content was observed at highest level of applied P in both the soil types. Additionally, the application of varying levels of Zn, either alone or combined with P, did not significantly affect Fe-P content in either soil type. Notably, the mean Fe-P content at each successive level of P application was higher in high P status soil compared to low P status soil.

**Table 5:** Effect of different levels of P and Zn on Fe-P content (mg kg<sup>-1</sup>) in low and high Olsen's P status soils

P levels (mg kg <sup>-1</sup> )	Zn levels (mg kg <sup>-1</sup> )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
0	24.59	23.09	23.91	22.47	23.52
30	36.24	34.05	34.69	35.99	35.24
60	41.59	39.50	40.18	38.12	39.85
120	65.35	62.19	63.63	61.33	63.12
180	83.96	83.43	82.23	80.05	82.42
Mean	50.35	48.45	48.93	47.59	
CD (p- 0.05)	P- 3.34		Zn- NS		PxZn- NS
<b>High P status soil</b>					
0	41.40	37.91	42.85	37.10	39.81
30	53.55	56.87	56.81	53.96	55.30
60	68.72	70.67	65.67	64.07	67.28
120	92.80	88.76	88.04	86.24	88.96
180	100.10	95.30	94.22	93.06	95.67
Mean	71.31	69.90	69.52	66.89	
CD (p- 0.05)	P- 4.11		Zn-NS		PxZn- NS

### Reductable (Red-P)

The data presented in Table 6 reveal a significant impact of graded P application on red-P content in both the soil types. It is evident that the mean red-P content increased from 22.21 to 81.19 mg kg<sup>-1</sup> in low P status soil and from 34.74 to 88.41 mg kg<sup>-1</sup> in high P status soil as P levels escalated from 0 to 180 mg kg<sup>-1</sup>. The highest average red-P content in both low P status soil (81.19 mg kg<sup>-1</sup>) and high P status soil (88.41 mg kg<sup>-1</sup>) was observed at the highest P application dose (180 mg kg<sup>-1</sup>). However, the application of various Zn levels, either alone or in combination with different P levels did not significantly influence red-P content in either soil type. Notably, a comparatively higher mean red-P content was observed in high P status soil as compared to low P status soil.

**Table 6:** Effect of different levels of P and Zn on red-P content (mg kg<sup>-1</sup>) in low and high Olsen's P status soils

P levels (mg kg <sup>-1</sup> )	Zn levels (mg kg <sup>-1</sup> )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
0	23.29	21.79	22.61	21.17	22.21
30	34.94	32.75	33.39	34.69	33.94
60	40.29	38.20	38.88	36.82	38.55
120	64.12	60.96	62.40	60.10	61.90
180	82.73	82.20	81.00	78.82	81.19
Mean	49.07	47.18	47.66	46.32	
CD (p- 0.05)	P- 3.18		Zn- NS		PxZn- NS
<b>High P status soil</b>					
0	36.32	32.83	37.77	32.02	34.74
30	48.47	51.79	51.73	48.88	50.22
60	63.64	65.59	60.59	58.99	62.20
120	87.72	83.68	82.96	81.16	83.88
180	89.01	88.71	88.54	87.38	88.41
Mean	65.03	64.52	64.32	61.69	
CD (p- 0.05)	P- 4.23		Zn-NS		PxZn- NS

### Calcium-P (Ca-P)

It is evident from the Table 7 that the application of various P levels significantly affected Ca-P content in both low and high P status soils. As the P levels increased from 0 to 180 mg kg<sup>-1</sup>, the mean Ca-P content increased significantly from 101.14 to 145.25 mg kg<sup>-1</sup> in low P status soil and from 153.95 to 244.77 mg kg<sup>-1</sup> in high P status soil. The highest Ca-P content was observed in both the soils at P level 180 mg kg<sup>-1</sup>. However, in both the soil types, the application of different Zn levels, either alone or in combination of different P levels, did not produce any significant effect on Ca-P content. Nevertheless, at each successive level of applied P, the quantity of Ca-P was found to be higher in high P status soil as compared to low P status soil.

### Organic-P (Org-P)

The data provided in Table 8 clearly demonstrate a significant impact of graded P doses on org-P content in soils with varying P statuses. With increasing levels of applied P from 0 to 180 mg kg<sup>-1</sup>, the average org-P content increased notably from 53.14 to 135.15 mg kg<sup>-1</sup> in low P status soil and from 71.33 to 240.68 mg kg<sup>-1</sup> in high P status soil. The maximum mean org-P content in both low P status soil (135.15 mg kg<sup>-1</sup>) and high P status soil (240.68 mg kg<sup>-1</sup>) was observed at P application level 180 mg kg<sup>-1</sup>. However, the application of different Zn levels, either alone or in combination of varying P levels, did not yield a significant effect on org-P content in either soil type. Nevertheless, it is worth noting that the mean org-P content at each successive level of applied P was

higher in high P status soil as compared to low P status soil.

**Table 7:** Effect of different levels of P and Zn on Ca-P content ( $\text{mg kg}^{-1}$ ) in low and high Olsen's P status soils

P levels ( $\text{mg kg}^{-1}$ )	Zn levels ( $\text{mg kg}^{-1}$ )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
0	100.45	101.66	100.28	102.15	101.14
30	116.40	118.80	118.80	116.88	117.72
60	128.00	126.80	124.00	123.00	125.45
120	135.00	135.00	134.00	138.00	135.50
180	149.00	148.00	144.00	140.00	145.25
Mean	125.77	126.05	124.22	124.01	
CD (p- 0.05)	P- 7.37	Zn- NS		PxZn- NS	
<b>High P status soil</b>					
0	158.80	145.90	158.80	152.30	153.95
30	190.20	188.00	186.30	181.20	186.43
60	220.10	237.30	230.60	228.47	229.12
120	240.40	236.20	232.73	230.10	234.86
180	251.60	248.20	243.40	235.89	244.77
Mean	212.22	211.12	210.37	205.59	
CD (p- 0.05)	P- 15.77	Zn- NS		PxZn- NS	

### Total-P

The data given in Table 9 clearly indicate that P application significantly influenced the total-P content in both low P status and high P status soil. It was observed that as P levels increase from 0 to 180  $\text{mg kg}^{-1}$ , Total-P content markedly rises from 228.47 to 536.17  $\text{mg kg}^{-1}$  in low P status soil and from 376.37 to 826.52  $\text{mg kg}^{-1}$  in high P status soil. The highest mean total-P content, reaching 536.17  $\text{mg kg}^{-1}$  in low P status soil and 826.52  $\text{mg kg}^{-1}$  in high P status soil, was recorded at P level 180  $\text{mg kg}^{-1}$ . However, the application of Zn, either alone or combination of graded doses, did not demonstrate any significant effect on total-P content in either type of soil. It is noteworthy that at each successive level of P application, the mean total-P content was higher in high P status soil.

**Table 8:** Effect of different levels of P and Zn on Org-P content ( $\text{mg kg}^{-1}$ ) in low and high Olsen's P status soils

P levels ( $\text{mg kg}^{-1}$ )	Zn levels ( $\text{mg kg}^{-1}$ )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
0	57.74	52.51	55.07	47.24	53.14
30	67.93	71.85	62.10	65.43	66.83
60	93.43	84.21	89.58	79.01	86.56
120	108.88	110.52	117.17	125.59	115.54
180	145.21	135.21	130.96	129.21	135.15
Mean	94.64	90.86	90.98	89.30	
CD (p- 0.05)	P- 6.73	Zn- NS		PxZn- NS	
<b>High P status soil</b>					
0	73.91	79.75	70.65	61.01	71.33
30	98.87	92.17	86.13	89.72	91.72

60	120.41	115.23	118.90	110.63	116.29
120	187.56	176.52	194.15	203.43	190.42
180	248.17	245.48	233.23	235.82	240.68
Mean	145.79	141.83	140.61	140.12	
CD (p- 0.05)	P- 10.83	Zn- NS		PxZn- NS	

**Table 9 :** Effect of different levels of P and Zn on total-P content ( $\text{mg kg}^{-1}$ ) in low and high Olsen's P status soils

P levels ( $\text{mg kg}^{-1}$ )	Zn levels ( $\text{mg kg}^{-1}$ )				Mean
	0	2.5	5	10	
<b>Low P status soil</b>					
0	234.19	228.59	230.31	220.77	228.47
30	291.94	295.25	286.89	291.34	291.36
60	345.99	332.16	337.18	321.87	334.30
120	447.85	441.09	448.19	452.76	447.47
180	558.18	541.13	528.73	516.65	536.17
Mean	375.63	367.65	366.26	360.68	
CD (p- 0.05)	P- 26.25	Zn- NS		PxZn- NS	
<b>High P status soil</b>					
0	385.00	373.21	384.48	362.78	376.37
30	505.70	506.31	494.45	487.54	498.50
60	594.93	612.82	596.30	580.65	596.18
120	749.38	734.75	730.95	740.58	738.91
180	851.82	835.45	815.49	803.33	826.52
Mean	617.36	612.51	604.34	594.98	
CD (p- 0.05)	P- 42.14	Zn- NS		PxZn- NS	

### Discussion

In low P status soil, the highest P uptake by grain ( $2.44 \text{ mg pot}^{-1}$ ) was achieved with the application of P 180  $\text{mg kg}^{-1}$  along with Zn 10  $\text{mg kg}^{-1}$ . Conversely, in high P status soil, while the interaction effect of P  $\times$  Zn on P uptake by grain and straw was found to be non-significant. The highest P uptake by grain ( $2.88 \text{ mg pot}^{-1}$ ) was observed with the application of P 180  $\text{mg kg}^{-1}$  along with Zn 10  $\text{mg kg}^{-1}$ . However, for straw, the maximum P uptake ( $0.33 \text{ mg pot}^{-1}$ ) was recorded at P 60  $\text{mg kg}^{-1}$  + Zn 10  $\text{mg Zn kg}^{-1}$  level. Similar results were also reported by Singh *et al.* (2004), Yang *et al.* (2010), Singh and Singh (2012) and Arshad *et al.* (2016). The higher uptake of P was recorded in high P status soil as compared to low P status soil. This can be due to as nutrient uptake is the product of yield (grain or straw) and nutrient concentration (P). Similar findings were also reported by Maurya *et al.* (2015) and Mishra *et al.* (2017), Mathpal *et al.* (2015) and Ghulam *et al.* (2009).

In both soil types, the concentration of all these fractions consistently rose with higher rates of P application. The maximum content of these fractions was observed when P was applied alone at its highest rate 180  $\text{mg kg}^{-1}$ . This aligns with similar findings reported by Kumar *et al.* (2013) and Chandrakala *et al.* (2017), suggesting that this phenomenon might be

attributed to the conversion of added P into various forms of unavailable P. These fractions exhibited higher concentration in high P status soil as compared to low P status soil. Same trend also noted by Nayak and Patel (2016). This difference could be attributed to variations in initial available P levels, organic matter content and soil texture. Ojo *et al.* (2015) further emphasized that differences in P fraction values were significantly influenced by soil types. The increase in P fertilization rates corresponding to an increase in P fraction was consistent with the findings of Murthy *et al.* (2002), Sihag *et al.* (2005), Setia and Sharma (2007) and Kaur *et al.* (2015).

The saloid-P content ranged from 2.82 to 18.04 mg kg<sup>-1</sup> in low P status soil and from 4.07 to 20.30 mg kg<sup>-1</sup> in high P status soil (Table 3). The higher amount of saloid-P levels in high P status soil could be attributed to the gradual conversion of initially applied soluble P forms into less soluble forms over time. This observation is consistent with the findings of Singh and Sharma (2007) and Singh *et al.* (2016). In low P status soil, the Al-P content ranged from 24.98 to 79.24 mg kg<sup>-1</sup>, while in high P status soil, it ranged from 70.34 to 142.64 mg kg<sup>-1</sup> (Table 4). Likewise, the Fe-P content was notably higher in high P status soil, ranging from 37.10 to 100.10 mg kg<sup>-1</sup> as compared to its range in low P status soil, which was from 22.47 to 83.96 mg kg<sup>-1</sup> (Table 5). The relatively higher presence of Al-P and Fe-P in high P status soil might be attributed to the presence of sesquioxides, which could have transformed a portion of the applied P into these forms. Red-P content varied from 21.17 to 82.73 mg kg<sup>-1</sup> in low P status soil and from 32.02 to 89.01 mg kg<sup>-1</sup> in high P status soil (Table 6). It is plausible that the increase in biomass and biological activity might have inhibited the formation of red-P, consequently leading to an increase in Ca-P and Al-P content, as suggested by Kaur *et al.* (2015). The Ca-P content ranged from 100.28 to 149.00 mg kg<sup>-1</sup> in low P status soil and from 152.30 to 251.60 mg kg<sup>-1</sup> in high P status soil (Table 7). The predominance of Ca-P among various P fractions could be attributed to the neutral pH and calcareous nature of the soil. This dominance aligns with the findings of Devra *et al.* (2014), who observed Ca-P as the dominant inorganic P fraction in Rajasthan soils characterized by high CaCO<sub>3</sub> and pH ranging from 7.04 to 9.98. In low P status soil, org-P content ranged from 47.24 to 145.21 mg kg<sup>-1</sup>, while in high P status soil, it ranged from 61.01 to 248.17 mg kg<sup>-1</sup> (Table 8). Variations in organic matter content, clay content and total-P content likely account for the differences in values between the two soils. These findings are consistent with those of Singh *et al.* (2016). Total-P content ranged from 220.77 to 558.18

mg kg<sup>-1</sup> in low P status soil and from 362.78 to 851.82 mg kg<sup>-1</sup> in high P status soil (Table 9). The higher total-P values in high P status soil might be attributed to its higher clay content as compared to low P status soil. Mahmood *et al.* (2003) also noted higher concentrations of total-P in heavy soil as compared to light soil. Among the various P fractions, Ca-P was the dominant form, while Saloid-P was present in the least amount in both the soils. This ordering of abundance, Ca-P > Org-P > Al-P > Fe-P > Red-P > Saloid-P, was consistent with the findings of Kaur *et al.* (2015), Singh and Sharma (2007) and Kalaivanan and Sudhir (2012). Similar trends in the abundance of different forms of P fractions were also reported by Chandrakala *et al.* (2017) and Patle *et al.* (2019).

### Conclusions

Based on this study it can be inferred that P application significantly enhances P uptake by wheat grain in both low and high P status soils, with the highest uptake observed at 180 mg P kg<sup>-1</sup> combined with 10 mg Zn kg<sup>-1</sup>. However, straw P uptake was maximized at a lower P application rate (60 mg P kg<sup>-1</sup> + 10 mg Zn kg<sup>-1</sup>). In high P status soil, P × Zn interaction has minimal impact, while straw uptake is maximized at a lower P level (60 mg P kg<sup>-1</sup> + 10 mg Zn kg<sup>-1</sup>). Since P uptake in wheat grain is maximized at 180 mg P kg<sup>-1</sup>, farmers should apply P strategically to ensure sufficient availability, especially in low P status soils where its impact is more pronounced. Increasing levels of P from 0 to 180 mg kg<sup>-1</sup> led to a significant increase in the various forms of P fractions in both the soils. The maximum content of these fractions was observed at highest dose of P in both types of soil. However, the effect of different levels of Zn and the interaction between P and Zn on different forms of P fractions was found to be non-significant in both soils. Among the various P fractions, Ca-P was the most dominant form, while Saloid-P was the least abundant form of P fraction in both the soils. The relative order of abundance of different forms of P fractions, Ca-P > Org-P > Al-P > Fe-P > Red-P > Saloid-P, remained consistent in both the soils.

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