academicJournals

Vol. 10(39), pp. 3782-3790, 24 September, 2015
DOI: 10.5897/AJAR2015.10209
Article Number: C65591A55601
ISSN 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

The rhizosphere effect of some wheat cultivars on inorganic phosphorus fractions in a phosphorus-deficient calcareous soil

Razieh Khalili-Rad and Hossein Mirseyed Hosseini*

Soil Science Department, Faculty of Agricultural and Environmental Sciences, University of Tehran, Karaj, Iran.

Received 24 July, 2015; Accepted 10 September, 2015

Knowledge of the distribution and changes of soil phosphorus fractions in the rhizosphere, helps to determine efficiency of different crop cultivars in phosphorus acquisition. This study was conducted in order to evaluate the rhizosphere effect of some wheat cultivars on inorganic phosphorus fractions. A greenhouse experiment as a factorial in completely randomized design was conducted with 10 treatments and 3 replications. Experimental factors were different plant cultivars (4 wheat cultivars and control) and soil-sampling zone (rhizosphere and non-rhizosphere). A rhizobag technique was used to separate rooted and non-rooted inside each pot representing the two soil sampling zones. Based on fractionation results, the order of inorganic phosphorus fractions in the studied soil were apatite-P> OCP-P> DCP-P> Al-P> Fe-P> O-P which were found to be in the order of 830, 123, 17, 16, 14 and 0 g kg^{-1}, respectively. The concentration of the most inorganic phosphorus fractions between rhizosphere and non-rhizosphere soil was significantly different. All plant cultivars decreased inorganic phosphorus forms significantly. This difference was not equal for all cultivars and all fractions. Organic P was significantly higher in the rhizosphere soil compared to non-rhizosphere soil. Soluble phosphorus was not significantly differed between rhizosphere and non-rhizosphere soil. Root induced chemical changes; root morphology, microbial populations, pH changes etc. can be determining factors on phosphorus depletion differences among plant cultivars and soil sampling zone.

Key words: Phosphorus, fractionation, rhizosphere, rhizobag, wheat.

INTRODUCTION

Phosphorus (P) is one of the most important essential macronutrients for plant growth in agricultural systems (Raghothama, 1999; Zhao et al., 2007). It plays a primary role in many of the physiological processes such as energy metabolism and biosynthesis of nucleic acids in plants and functions in very important process like photosynthesis, respiration, and regulation of a number of enzymes (Vance et al., 2003; Caldecott, 2009).

Due to limited sources of P in the world and regarding to P character as a low mobile and low available element in soil, P is a major limiting factor of plant growth in cropping systems (Hinsinger, 2001; Lambers et al.,

*Corresponding author. E-mail: hmirseyed@yahoo.com, mirseyed@ut.ac.ir, Tel/Fax: 0098-2632231787.

2006). Owing to this restricted movement, the utilization efficiency of P fertilizer by plant is very low and its recovery ranges from 15 to 25% (Nisar, 1985). A part of applied P fertilizer in soil, goes to soil solution and taken up by plants, while the rest either precipitates or is adsorbed by exchange sites in the soil (Hinsinger, 2001). The most amount of P reaches to plant roots by diffusion (Rengel, 1993; Jaillard et al., 2000) and P diffusion coefficient (D_e) is very low (10^{-12} to 10^{-15} m^2 s^{-1} otherwise its fixation rate in soil is high (Morgan, 1997; Sylvia et al., 2005). In fact, not only P can be dominantly adsorbed by Al/Fe oxides and hydroxides in acid soils, but also can be adsorbed on the surface of Ca carbonate and clay minerals in neutral-to-calcareous soils (Lindsay et al., 1989; Parfitt, 1989). Concentration gradient and diffusivity of P in the soil near the roots determines P absorption by plants. One of the most important factors in generating this concentration gradient is root-soil interaction in the rhizosphere (Marschner, 1995; Hinsinger, 2001). Chemical and biological changes in the rhizosphere induced by roots, is a determining factor in bioavailability of soil P and an important key for optimizing P management to improve P-use efficiency in crop production. Therefore, better perspective of P dynamic in the soil-rhizosphere-plant complex continuum is necessary for achieving this purpose (Shen et al., 2011).

Sequential fractionations methods can help to access some information about the bounded forms of soil inorganic P (BaRančíková et al., 2007). It is an attempt to separate P pools according to their lability (Abekoe, 1996). It can be used to study the effect of management system on soil P (Negassa and Leinweber, 2009). Single or combined chemical reagents are used to extract particular P fractions. There are not many studies that relate these fractions directly to their bioavailability (Brezonik et al., 2000).

Soil properties, source and amount of applied P fertilizer, plant species, crop rotation etc. are some factors that affect or redistribute all P fractions in soil. Possible difference among species or cultivars in P uptake and recognizing plants potential to change soil inorganic P and its acquisition will expectantly be effective on reducing cost of P fertilization and will increase applied fertilizer recovery as well as plant productivity with using more P efficient plants (Gahonia et al., 1999).

Distribution of inorganic and organic P fractions in two soils as affected by crop species (soybean, white lupin, and maize) and nitrogen applications was investigated by Qiao (2012) and was reported that the percentage of total P present as inorganic P was affected by crop species, soil type, and N source but the moderately labile organic P was not affected significantly. This investigator mentioned that correct choice of crop species and the application of a suitable N source may increase crop yield and P uptake by plant in P-deficient soils. Changes in P fractions in the rhizosphere of some crop species under glasshouse conditions was investigated by Safari Sinegani and Rashidi (2011). These authors reported a decrease in all inorganic P forms by all plant species in rhizosphere compared to non-rhizosphere soil. Similarly, it was reported that inorganic P forms decreased in the rhizosphere of three tea cultivars, while increasing in microbial activity and transformation of inorganic dissolved P to organic phosphorus caused an increase at the amount of organic P (Zoysa et al., 1999).

Mineral nutrition of plants, specially P and micronutrients as low mobile elements in soils, can be affected by rhizosphere processes through modifying nutrient solubility in soil close (1-2 mm) to absorbing roots (Gahoonia and Nielsen, 1991).

Study of rhizosphere soil mainly is technically difficult due to the thin soil layer directly influenced by roots and the wide root distribution (Hylander, 2002). Based on the aims and facilities provided, different methods (gentle shaking and using a soft brush) and techniques (different types of devices such as rhizobox and rhizobag), had been proposed for studying chemical changes in the rhizosphere (Riley and barber, 1969; Cappy and Brown 1980; Kuchenbuch and Jungk, 1982; Youssef and Chino 1988; Gahoonia and Nielsen 1991; Wenzel et al., 2001).

The aim of study, type of plants investigated and whether they are cultivated in containers or in the field are some determining factors to choose the procedure followed to obtain rhizosphere and bulk soils (Corti et al., 2005). Restricting the root growth to a certain soil volume will create a higher root density and facilitate sampling of rhizosphere soil. However, each method has its own advantages and disadvantages and the differences and precision of each method for sampling the rhizosphere soil need to be studied more.

Understanding the quantity and significance of different soil P forms is important for proper soil fertility management especially for calcareous soils. Making long term environmentally sound agricultural decisions requires knowledge of the availability of soil P forms for plant species and cultivars. The objective of this study was to investigate the status of different inorganic P forms in the rhizosphere. Soil inorganic P around the roots of four wheat cultivars, as rhizosphere soil, were compared to P inorganic forms in non-rhizosphere soil using rhizobag technique.

MATERIALS AND METHODS

Soil sampling

A surface soil (0-30 cm) with low available P (<5 mg kg^{-1}) was sampled from the agricultural research station fields (36° 15´ 17´´ N, 49° 54´ 28´´ E) in Qazvin province (Northern Iran) with annual rainfall 310 to 320 mm and annual average temperature 9°C. The soil used was a Coarse loamy, mixed, thermic, Typic Xerofluvents. Illite, Colorite, Smectite and fewer amounts of Kaolinite and Quartz were the dominant clay minerals in the site.

Soil physical and chemical analyses

The soil sample was air-dried and ground to pass through a 2 mm sieve for laboratory experiments. Selected soil properties were determined according to standard methods (Sparks, 1996). Soil particles contents (sand, silt and clay) were separated using hydrometer method; Equivalent calcium carbonate (ECC) was measured by back-titration procedure. Soil pH and electrical conductivity (EC) was measured in a saturated paste and saturated extract, respectively. Organic carbon (OC) was analyzed by dichromate oxidation and titration with ferrous ammonium sulfate. Total nitrogen (N) was determined by the Kjeldahl method. Available Potassium (K) was extracted from the soil by ammonium acetate 1 normal pH=7 and measured by flame photometer.

Available P (Olsen-P) was extracted using 0.5 M sodium bicarbonate solution at pH=8.5 and determined using spectrophotometer as blue molybdate-phosphate complexes under partial reduction with ascorbic acid (Jackson, 1958). Soluble P in water, total P by perchloric acid ($HClO_4$) digestion and organic P according to Kou (1996) were also determined according to standard methods.

Method described by Jiang and Gu (1989) was used to determine different forms of soil inorganic P. Sequentially soil di-Ca-phosphates (DCP-P) in 0.25 M $NaHCO_3$ (pH=7.5), octa-Ca-phosphates (OCP-P) in NH_4OAC 0.5 M (pH=4.2), Al phosphates (Al-P) in 0.5 M NH_4F (pH=8.2), Fe phosphates (Fe-P) in 0.1 N NaOH-0.1 N Na_2CO_3, occluded P (O-P) in 0.3 M Na_3-Cit-$Na_2S_2O_4$-NaOH, and P as apatite (apatite-P) in 0.5 N H_2SO_4 were extracted and determined with spectrophotometer.

Plant culture and rhizosphere-study technique

Plastic pots with 15 cm height and 10 cm opening mouth diameter were selected. Each pot was filled with approximately 1.7 kg of air-dried soil passed through a 4 mm sieve. The soil moisture was held constant at field capacity by weighting pots and adding appropriate volumes of di-ionized water. The soil was amended with basal nutrients such as 100 mg kg^{-1} N (as Urea) in two splits, 50 mg kg^{-1} K (as K_2SO_4), 30 mg kg^{-1} Mg (as $MgSO_4$, $7H_2O$), 5 mg kg^{-1} Fe (as sequestrene-138) and 0.5 mg kg^{-1} B (as H_3BO_3).

A rhizobag technique was used for separating rhizosphere soil. In this technique, certain content of the prepared soil was filled into a nylon bag with a certain mesh size, restricting growth of roots from the outer compartment. Then, these rhizobags were placed in the center of plastic buckets and surrounded by the soil so that soil surfaces inside and outside the bags were at equal levels (McGrath, 1997; Silva Gonzaga et al., 2006). In this study, a cylindrical rhizobags (12×6 cm) was made of nylon with a mesh size of 60 µm and used to sample rhizosphere and non-rhizosphere soil. The content of soil inside of each rhizobag was about 380 g.

In each pot five seeds were sown in the rhizobag. Four days after germination seedling were reduced uniformly to three per pot. Four cultivars of *Triticum aestivum* (Azadi, Yavarus, Karaj 1 and Marvdasht) were grown in a controlled greenhouse conditions and were grown in total for 6 weeks. The control treatment was unplanted soil.

At harvest (after six weeks), plant roots were separated carefully and soil material inside and outside the rhizobag was taken as rhizosphere and non-rhizosphere soil, respectively. Soluble and Olsen P, DCP-P, OCP-P, Al-P, Fe-P, apatite-P, and total P were measured in the rhizosphere and non-rhizosphere soils. The rhizosphere and non-rhizosphere soil pH were measured in a 1:5 soil to water extract after shaking 30 min (Hesse, 1971). Moreover, two series of pots with and without P fertilizer application were prepared. Six weeks After planting of four above mentioned wheat cultivars, some root morphological properties (total root length, root surface area, root volume, wet and dry weight of roots) were measured and shoot to root ratio was calculated (Newman, 1966; Bohm, 1979). Furthermore, shoot P concentration (PC) was assayed using the vanadomolybdate method (Westerman, 1990) and shoot total P uptake (TP), P acquisition efficiency (PAE) and P efficiency (PE) was calculated using following formula.

$TP = PC \times SDW$
$PAE = [TP \text{ in } P_0 / TP \text{ in } P_{20}] \times 100$
$PE = [SDW \text{ in } P_0 / SDW \text{ in } P_{20}] \times 100$

Statistical analyses

The experiment was considered a completely randomized design as factorial in 3 replicates. In fractionation experiment, the factors were plant cultivars (4 wheat cultivars and control) and soil sampling zone (soil inside and outside the rhizobag as rhizosphere and non-rhizosphere soil). In experiment related to root morphological properties and plant efficiency indexes, the factors were plant cultivars (4 wheat cultivars) and P fertilizer application (no fertilizer and 20 mg kg^{-1} P fertilizer considered as efficient amount). Data were statistically analyzed by SAS software. Duncan's new multiple range tests were performed to assess the effect of plant cultivars and sampling zone on soluble and Olsen P, DCP-P, OCP-P, Al-P, Fe-P, apatite-P, and total P.

RESULTS AND DISCUSSION

Soil properties

Table 1 shows some physical and chemical characteristics of soil used in the experiment. According to soil fractionation results determined by Jiang and Gu (1989) method, the contents of different P forms in the studied soil were 15.53 mg kg^{-1} for DCP-P, 114.5 mg kg^{-1} for OCP-P, 14.67 mg kg^{-1} for Al-P, 13.02 mg kg^{-1} for Fe-P, 770.1 for P as apatite (apatite-P), and 0 mg kg^{-1} for O-P. The amount of total P, soluble P and organic P in studied soil were 1091.9 and 2.78, 123.5 mg kg^{-1}, respectively.

As mentioned previously, apatite-P (83%) and OCP-P (12.3 %) were the predominant soil inorganic P forms in this soil. The amount of O-P fraction in the studied soil was negligible. With respect to the sampling location, this result is in accordance with other studies (Mostashari et al., 2008; Safari Sinegani and Rashidi, 2011). The percentages of P fractions in the planted and control soils from Hydare fields in Hamadan province (NW Iran) studied by Safari Sinegani and Rashidi (2011) were near 640 g kg^{-1} apatite-P, 240 g kg^{-1} OCP-P, 70 g kg^{-1} Fe-P, 40 g kg^{-1} DCP-P, 10 g kg^{-1} Al-P, and 0 g kg^{-1} O-P. Mostashari et al. (2008) examined the amount of different P forms, that is, DCP-P, OCP-P, Al-P, Fe-P, O-P, and P as apatite in some calcareous soils of Qazvin province and reported to be in the range of: 1.6-42.3, 72-314, 14.5-54.8, 8.4-34.8, 5.9-33.4 and 262-697 mg kg^{-1}, respectively.

The effects of plant cultivars on soil inorganic P fractions

The effect of plant cultivars on soil soluble P, total P,

Table 1. Some physical and chemical properties of used soil

ECC	OC	EC	pH in saturated mud	FC	SP	Soil texture	Clay	Silt	Sand
(g kg^{-1})		(ds m^{-1})		(%)				(%)	
70	4.7	1.489	7.45	17	34	Sandy loam	19	24	57
Cu	**Mn**	**Zn**	**Fe**	**Mg**	**Ca**	**K**	**P**	**Total N**	
		(mg kg^{-1})		**(mg l^{-1})**		**(mg kg^{-1})**		**(g kg^{-1})**	
1.1	10.4	0.76	2.07	16.92	229.2	298.8	4.65	0.5	

Table 2. Analysis of variance of the effect of plant cultivars (PC) and soil-sampling zone (SSZ) on inorganic P fractions, Olsen-P, soluble P and total P after plant harvest.

	DF	Olsen-P	Soluble P	DCP-P	OCP-P	Al-P	Fe-P	Apatite-P	Total P
		MS							
SSZ	1	0.9575**	0.0110 ^{ns}	25.2397**	3799.7893**	0.6714 ^{ns}	37.3572**	1578.9071*	4483.0**
PC	4	5.6162**	0.1988**	110.8305**	1105.4501**	27.6873**	29.7321**	4731.0161**	4544.0**
SSZ*PC	4	0.1933^{ns}	0.0002 ^{ns}	3.5249**	309.5875**	0.0445 ^{ns}	2.4054 ^{ns}	402.8216 ^{ns}	2232.7**
Error	20	0.0304	0.0069	0.7633	22.2904	0.5322	0.9825	217.7186	72.398

*, Mean square (MS) of the treatment is significant at the 0.05 level; **, significant at the 0.01 level; ns, not significant.

Table 3. Soil inorganic P fractions, Olsen P, soluble P and total P as affected by plant cultivars (n=6).

	Olsen-P	Soluble P	DCP-P	OCP-P	Al-P	Fe-P	Apatite-P	Total P
	(mg kg^{-1})							
Azadi	1.15^{d}	1.43^{b}	4.98^{d}	79.30^{d}	8.58^{c}	7.13^{d}	694.60^{d}	1018.0^{c}
Yavarus	1.50^{c}	1.73^{a}	7.59^{c}	90.61^{c}	12.69^{a}	8.62^{c}	723.52^{bc}	1073.1^{b}
Karaj 1	1.43^{c}	1.46^{b}	6.54	83.77^{d}	10.34^{b}	8.22^{cd}	711.77^{cd}	1071.0^{b}
Marvdasht	2.05^{b}	1.76^{a}	12.51^{b}	97.41^{b}	13.25^{a}	10.51^{b}	732.63^{b}	1068.2^{b}
Control	3.57^{a}	1.83^{a}	15.17^{a}	113.95^{a}	13.57^{a}	12.78^{a}	769.78^{a}	1091.6^{a}

Means followed by the same letter in each column are not significantly different ($p<0.05$).

Olsen-P and soil inorganic P fractions (Table 2) revealed that the effect of plant cultivars on soluble P, total P, Olsen-P, DCP-P, OCP-P, Al-P, Fe-P, and apatite-P was significant ($p<0.01$).

The results of Duncan's new multiple range tests of means of soil soluble P, total P, Olsen-P and soil inorganic P fractions as affected by plant cultivars has been shown in Table 3. Unplanted soil (control) had the highest amount of soluble P, Olsen-P, total P, and different soil inorganic P fractions, that is, DCP-P, OCP-P, Al-P, Fe-P, and P as apatite. Soil soluble P, total P, Olsen-P and soil inorganic P fractions were decreased significantly by plants ($p<0.05$). Although, the decrease of these P forms in the rhizosphere soil was not equal for each fraction.

Soil planted with Azadi and Marvdasht cultivars had the lowest and the highest amount of mentioned P forms, respectively (Table 3). Azadi as a P-efficient cultivar had higher ability to decrease different soil P forms. For example, soil P as apatite decreased from 769.78 mg kg^{-1} in unplanted soil to 694.60 mg kg^{-1} in soil planted with Azadi cultivar (Table 3).

However, all plant cultivars decreased soluble P and Al-P, but the amounts of these fractions in soil planted with Yavarus and Marvdasht cultivars were not significantly ($p<0.05$) different from that in control soil.

Apatite-P had the most considerable decrease (from 769.78 mg kg^{-1} in unplanted soil to about 673.36 mg kg^{-1} in Azadi cultivar) in the rhizosphere soil in comparison to DCP-P, OCP-P, Al-P and Fe-P (Table 7). The ability of Azadi cultivar to take up P from different forms through redistribution was the highest among the tested cultivars.

Reversely, the lowest amount (120.73 mg kg^{-1}) of organic P was observed in unplanted soil (control) and all wheat cultivars increased organic P, significantly ($p<0.05$). Azadi cultivar had the highest amount (139.31 mg kg^{-1}) of organic P and mean of organic P in Yavarus, Karaj 1 and Marvdasht cultivars were 138.77, 136.48 and

Table 4. Root morphological properties as affected by plant cultivars (n=6) and phosphorus fertilizer levels (n=12).

	Root wet weight (g)	Root dry weight (g)	Shoot dry weight (g)	Shoot to root ratio	Total root length (cm)	Root surface area (cm^2)	Root volume (cc)
Azadi	2.269^a	0.313^a	0.727^a	2.319^b	278.42^a	90.17^a	2.333^a
Yavarus	1.784^b	0.252^b	0.695^a	2.770^a	223.84^b	75.92^b	2.050^b
Karaj 1	1.967^b	0.260^b	0.611^b	2.313^b	231.55^b	79.39^b	2.167^{ab}
Marvdasht	1.283^c	0.201^c	0.588^b	3.041^a	179.04^c	56.06^c	1.417^c
No P fertilizer	1.311^b	0.182^b	0.447^b	2.507^a	161.54^b	54.39^b	1.467^b
Optimum level of P fertilizer	2.340^a	0.331^a	0.864^a	2.714^a	294.89^a	96.38^a	2.517^a

Means followed by the same letter in each column are not significantly different ($p<0.05$).

Table 5. Efficiency indexes as affected by plant cultivars (n=6) and phosphorus fertilizer levels (n=12).

	Shoot P concentration (mg/g)	Shoot total P uptake (mg/pot)	Phosphorus efficiency (%)	Phosphorus acquisition efficiency (%)
Azadi	3.294^a	2.572^a	57.32^a	32.90^a
Yavarus	2.608^c	1.946^b	56.51^a	32.75^a
Karaj 1	2.746^b	1.822^c	47.48^{ab}	29.10^{ab}
Marvdasht	2.046d	1.348d	44.60^b	23.44^b
No P fertilizer	1.953^b	0.892^b	-	-
Optimum level of P fertilizer	3.394^a	2.951^a	-	-

Means followed by the same letter in each column are not significantly different ($p<0.05$).

131.21 mg kg^{-1}, respectively.

Assessing root morphological properties (total root length, root surface area, root volume, wet and dry weight of roots) of studied cultivars with and without P fertilizer application, revealed stronger and more extensive root system in Azadi cultivar compared to the others (Table 4). Also, this cultivar had higher dry weight of shoots, shoot to root ratio, shoot P concentration and shoot total P uptake as well as phosphorus acquisition efficiency and phosphorus efficiency (Tables 4 and 5).

Soil pH values in the rhizosphere of all four studied wheat cultivars were significantly ($p<0.05$) lower than those in the corresponding non-rhizosphere soil (Figure 1). The decrease of soil pH in the rhizosphere of studied wheat cultivars was between 0.12 and 0.38. In particular, decrease of soil pH in the rhizosphere of Azadi cultivar (0.38 units) was sharper than those in the rhizosphere of the other three cultivars. The decrease of soil pH in the rhizosphere of Yavarus and Karaj 1 cultivar were about 0.25 and 0.15 units respectively. Finally, Marvdasht cultivar had the least effect on soil pH (0.12 units). Mean of soil pH in the rhizosphere and non-rhizosphere soil were about 8.19 and 8.37, respectively.

Based on Jiang et al. (2010) investigation, plant species differ in their ability to take up P from the soil and these differences were attributed to the morphology and physiology of plants. Adventitious root angle, root surface area and root volume were defined as some indexes for low-P tolerant genotypes during the seedling stage.

Root secretions and associated soil microorganisms can directly affect the narrow region of soil which is defined as rhizosphere. The biological, chemical and physical activities in this region are different from bulk soil (Ma et al., 2009). The effect of root-associated factors such as ability to modify the rhizosphere using different mechanisms (root exudation of amino acids, organic acids, proton, acid phosphatase etc.), root morphology and architecture, root-hair density on inorganic P acquisition has been reported by many researchers (Hinsinger, 2001; Vance et al., 2003; Lambers et al., 2006; Richardson et al., 2009; Zhang et al., 2010; Shen et al., 2011). The results of investigation about the status of inorganic P fractions in the rhizosphere of some xerophytic shrubs in the Alxa desert showed soil inorganic P fractions were significantly affected by root activities. A decrease in soil pH in the rhizosphere ranges from 0.4-0.8 units has been reported in this investigation. These shrubs had different ability in acquiring P based on their ability to acidify the rhizosphere soil (Ma et al., 2009).

The effects of sampling zone on inorganic P fractions

The effect of soil sampling zone on soil soluble P, total P, Olsen-P and soil inorganic P fractions (Table 2) revealed

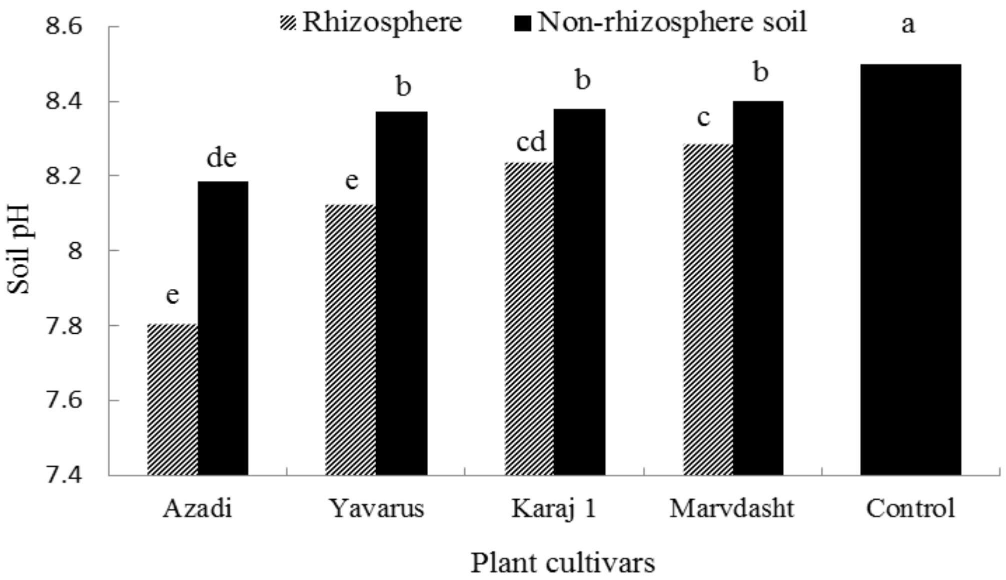

Figure 1. Soil pH in the rhizosphere and non- rhizosphere soil of different wheat cultivars. Means followed by the same letter are not significantly different ($p<0.05$).

Table 6. Soil inorganic P fractions, Olsen-P, soluble P and total P as affected by soil-sampling zone (n=15).

Sample zone	Olsen-P	Soluble P	DCP-P	OCP-P	Al-P	Fe-P	Apatite-P	Total P
				(mg kg^{-1})				
Rhizosphere soil	1.76^{b}	1.62^{a}	8.44^{b}	81.75^{b}	11.54^{a}	8.34^{b}	719.20^{b}	1052.2^{b}
Non-rhizosphere soil	2.12^{a}	1.66^{a}	10.28^{a}	104.26^{a}	11.84^{a}	10.57^{a}	733.71^{a}	1076.61^{a}

Means followed by the same letter in each column are not significantly different ($p<0.05$).

Table 7. The amounts of different soil P fractions in the rhizosphere and non-rhizosphere soil of studied cultivars.

	DCP-P		OCP-P		Al-P		Fe-P		Apatite-P		Organic P		Total P		Available P	
								(mg kg^{-1})								
	R	B	R	B	R	B	R	B	R	B	R	B	R	B	R	B
Azadi	4.6	5.3	70	88	8.4	8.8	5.7	8.6	673	716	144	135	972	1064	1.08	1.22
Yavarus	6.7	8.5	72	109	12.5	12.9	7.2	10.0	720	727	143	135	1065	1081	1.04	2.00
Karaj 1	5.1	8.0	71	97	10.2	10.5	6.7	9.7	705	718	138	135	1065	1077	1.29	1.57
Marvdasht	10.6	14.4	82	113	13.0	13.5	9.3	11.7	727	738	133	129	1067	1069	2.84	3.27
Control	15.2		114		13.6		12.8		770		121		1092		3.57	

R and B show rhizosphere and non-rhizosphere soil, respectively.

that the effect of soil sampling zone on Olsen-P, total P, DCP-P, OCP-P, and Fe-P was significant ($p<0.01$). In the case of apatite-P this effect was significant at the 0.05 level and there was no significant effect in the case of soluble P and Al-P.

The concentrations of total P and Olsen-P were significantly ($p<0.05$) lower in the rhizosphere than those in corresponding non-rhizosphere soils. There was no significant difference in the case of soluble P between rhizosphere and non-rhizosphere soil (Table 6).

Ca-P fractions (apatite-P and OCP-P) were the highest proportions in the rhizosphere. Compared to Fe-P, the content of Al-P was higher in the rhizosphere soil, as well. The concentrations of all soil inorganic P fractions, except Al-P, varied significantly ($p<0.05$) between rhizosphere and non-rhizosphere soils (Table 6). The results of mean comparison have shown that, although the amounts of soluble P and Al-P in different sampling zones were not significantly different, same as the other inorganic P forms, these forms of soil P were lower in the rhizosphere soil compared to non-rhizosphere soil. This indicates the considerable influence of the rhizosphere of plant cultivars on different inorganic P forms.

Orders of inorganic P fractions in the non-rhizosphere soil were apatite-P> OCP-P> Al-P> Fe-P> DCP-P> O-P with 842.7, 119.8, 13.6, 12.1, 11.8and 0 g kg^{-1}, respectively and orders of inorganic P fractions in the rhizosphere soil were apatite-P> OCP-P> Al-P> DCP-P> Fe-P> O-P which was found to be in the order of 867.3, 98.6, 13.9, 10.2, 10.0 and 0 g kg^{-1}, respectively.

Mean of organic P in the rhizosphere soil was higher compared to non-rhizosphere soil. Mean of this fraction in the rhizosphere and non-rhizosphere soil were 136 and 131 mg kg^{-1}, respectively. The decrease of Olsen-P in the rhizosphere which is in accordance with the results of other researchers (Jianguo and Shuman, 1991; Hanafi and Ng, 1996; Shen et al., 2004) showed Olsen-P depletion in the rhizosphere and it is related to absorption of Olsen-P by plants. In general, the mean of Olsen-P in the rhizosphere and non-rhizosphere soils were 1.8 and 2.1 mg kg^{-1}, respectively (Table 6). Total plant available P in soil can be considered as the remained available P in soil after plant harvest plus absorbed P by plants (roots and aerial bodies). Bagayoko et al. (2000) cultivated some cereals and legumes species in severely P-deficient acid sandy soils to measure changes in nutrient availability as affected by distance from the root surface and reported that available P in the rhizoplane was between 190 and 270% higher compared to the non-rhizosphere soil.

The decrease of acid extractable P (apatite-P) in the rhizosphere can be related to root induced chemical changes and microbial activities that contribute to transformation of this form of P to moderately or highly soluble and available P forms such as DCP-P and OCP-P. Najafi and Towfighi (2006) investigated the effects of rhizosphere of rice plant on the inorganic P fractions in the paddy soils and reported the decrease of apatite in treatments without P fertilizer application in most studied soils.

Soil pH decrease in the rhizosphere that has been reported by other researchers (Neumann and Römheld, 1999; Wang et al., 2006; Ma et al., 2009) can solve Ca phosphates such as DCP-P and OCP-P. The decrease of recent P forms in the rhizosphere shows that these P forms can be available as inorganic P forms for wheat. Based on Zhang et al. (2004) reports, reduction rate of DCP-P was the highest among all fractions while soil pH was decreased. Ma et al. (2009) also reported the decrease of DCP-P in the rhizosphere of some studied shrubs.

The decrease in Fe-P in the rhizosphere which is in accordance with the result of Safari Sinegani and Rashidi (2011) revealed that despite low content of Fe-P in calcareous soils, plant species can also use these forms of soil P. P and Fe uptake by plants decreases their concentration in the rhizosphere which follows by Fe-P release in solution, then recent P is absorbed by plant roots.

No significant difference in soluble P between rhizosphere and nonrhizosphere soil has been reported by Najafi and Towfighi (2006) and Safari Sinegani and Rashidi (2011). It seems there is a dynamic relationship among different P forms that buffer soluble P in the rhizosphere and compensate the soluble P uptake by plants. Otherwise soluble P, which is very low in the soil solution, cannot cover plants P requirements.

Generally has been reported that pH changes in the rhizosphere has a strong effect on bioavailability of soil P dynamics. Also, because of the possible effect of organic compounds on the rate and forms of inorganic P in calcareous soils, the effects of organic matter in the rhizosphere should be taken into account (Hinsinger, 2001). Moreover, microbial populations, phosphatase activity, root exudations and root morphology (root density, root surface area, root-hair length and density) and root-soil interactions in the rhizosphere can be determining factors on P depletion differences among plant species and different cultivars (Lambers et al., 2006; Richardson, 2009). As mentioned before, more root density was observed in Azadi cultivar in this study. This means more soil accessibility by the roots of this cultivar and more P efficiency.

Conclusion

Changes in different P forms in the rhizosphere of different wheat cultivars were observed in this study compared to the non-rhizosphere soil. However, these changes were not equal for all cultivars and all forms. Generally, Azadi cultivar with greater root development and higher phosphorus uptake depleted more inorganic P from the rhizosphere compared to other cultivars. Karaj 1 and Yavarus were the next cultivars which had the most effect on redistribution of inorganic P forms in the rhizosphere and finally, Marvdasht cultivar had the lowest effect on inorganic P forms in the rhizosphere. The changes in different P forms in the rhizosphere of studied cultivars might be a response of the cultivar differences in respect to root morphology and soil accessibility. Apatite-P and OCP-P had the highest proportion in both rhizosphere and non-rhizosphere soil. Compared to non-rhizosphere soil, most inorganic P fractions decreased significantly in the rhizosphere soil. Understanding P dynamics in the soil-rhizosphere-plant complex continuum can be useful in better management of P nutrition to save limited P resources and to maintain the quality of our environment. The right selection of the species or cultivars can also improve crop production and the uptake of P in P-deficient soils.

Conflict of Interest

The authors have not declared any conflict of interest.

ACKNOWLEDGEMENT

The financial support of the University of Tehran is thankfully acknowledged.

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