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Effect of arbuscular mycorrhizal fungus, plant growth promoting rhizobacterium, and soil drying on different forms of potassium and clay mineral changes in a calcareous soil under maize planting

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ABSTRACT- Greenhouse experiment was conducted in factorial experiment arranged as a completely randomized design (CRD) to evaluate the effect of *Glomus intraradices*, *Pseudomonas fluorescence* and soil drying on different forms of potassium (K) and the changes of clay minerals in a calcareous soil after maize planting. Treatments consisted of arbuscular mycorrhizal (AM) fungus at two levels: G_0 (not inoculated with fungus) and G_1 (inoculated with *Glomus intraradices*), bacteria at two levels B_0 (not inoculated with bacterium) and B_1 (inoculated with *Pseudomonas fluorescence*) and soil drying levels or four irrigation intervals of 2 (S_0), 4(S_1), 6(S_2) and 8(S_3) days. As soil drying increased, all forms of K increased and root colonization decreased. Inoculation of plants with microbial inoculants increased root colonization percentage and all forms of K in soil as compared to non microbial treatments. However, the effect of single inoculation with bacterium was less pronounced. Co-inoculation treatments of plants with fungus and bacterium resulted in the maximum amounts of root colonization and K forms as compared to single inoculation of plants with each inoculum. The amount of illite-chlorite minerals increased as soil dryinglevels increased. In non mycorrhizal treatments, there were no smectite minerals, while in mycorrhizal treatments, the quantity of smectite minerals increased as the levels of soil dryingincreased. It might be concluded that biofertilizers and soil drying are effective in minerals weathering and dissolution and K releasing.

INTRODUCTION

Potassium (K) is an essential nutrient element for plant growth whose importance in agriculture is well recognized (Sparks and Huang, 1985). Distribution of K forms differs from soil to soil. Soil total K reserves are generally large as a function of the dominant soil minerals present. Soil K is typically divided into four interrelated forms: water soluble, exchangeable, non-exchangeable, and structural K. Dynamic equilibrium reactions exist between different forms of K. The quantities of water soluble and exchangeable K forms are generally low and defined as plant readily available K. They occupy a small part of total K. Exchangeable K is weakly sorbed to the surfaces of soil particles and can rapidly replenish solution K. The amount of non-exchangeable K in soil is greatly affected by the clay content and the types of clay minerals that are present. For optimal nutrition of crops, the replenishment of a K-depleted soil solution is affected predominantly by the release of non-exchangeable K from clay minerals. Non-exchangeable K pool becomes available (at low exchangeable levels) for plant uptake while structural K can very slowly become available to plant through weathering (Sparks and Huang, 1985; Sparks, 1987).

Soil K is located mainly in minerals such as micas, feldspars, and their weathering products (Manning, 2009). Fixation and release depend on the level of K in soil solution, the type of clay minerals present in the soil, wetting and drying (Steffens & Sparks, 1997), biological processes, and substances secreted from the roots of plants (Martin and Sparks, 1985; Goulding, 1987; Hinsinger and Jaillard, 1993; Naderizadeh et al., 2010). Potassium can be released either by transformation into 2:1 expandable layer silicates or by dissolution (Zhou and Huang, 2007). Potassium release through mineral dissolution occurring especially in the rhizosphere and in the immediate vicinity of fertilizer zones (Huang et al., 2005) is more complex than the release through transformation of illite into 2:1 expandable layer silicates. Favorable drainage, enough leaching, and suitable weathering are factors that can strongly influence the release of K from illite, resulting in transformation of illite into other minerals, mainly smectite (Borchardt, 1989; Aoudjit et al., 1995).

Soil drying and microbial activity are important factors affecting chemical weathering and dissolution of minerals. Two competing processes may occur through drying: fixation occurs in wedge zones, while exfoliation of layers releases K. The net result could be K release or fixation, depending on the dominant process (Olk et al., 1995). Jia and Marion (2003) examined the release of K from air-

dried soil samples. They concluded that the value of soil exchangeable K increased after drying the soil samples and that the samples ith more mica and montmorillonite had higher exchangeable K in comparison with gibbsite and kaolinite.

Soil fertility management through the use of biological fertilizers is one of the crucial components in the sustainable agriculture system (Alexandratos, 2003). Plant growth promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) by using different mechanisms such as production of siderophores, organic acids, proton, growth regulators, and other chelating agents, and creative of reductive conditions, increase dissolution of minerals and mobility of non-soluble nutrients and thus improve nutrients uptake and yield of plants. They can influence plant root morphology and change the quantity and quality of root exudates. Inoculation of soybean roots with mycorrhizal fungi accelerated the weathering of biotites and the phologopite, but no effect was observed on the muscovite in the mycorrhizosphere of soybeans. Electron microprobe analysis also showed extensive removal of K from edges of the readily weathered biotite flakes subjected to biological weathering (Mojallali and Weed, 1978). Inoculation of pine (*Pinus sylvestris* L.) roots with acid-producing rhizobacteria (*Agrobacterium* sp.) increased cation-exchange capacity and loss of K from a mica (phlogopite) flakes. Electron microscopic observation with a microprobe demonstrated that K losses were greater for the phlogopite particles closely attached to the mycorrhizae. The mycorrhizal effect was attributed to an increase of exchange surface area, rather than to an increase in acidification. Co-inoculation of pine with bacterium and mycorrhiza significantly promoted mycorrhizal infection and phlogopite cation-exchange capacity, compared with a single inoculation with the bacterium or the fungus (Leyval and Berthelin, 1991). Arbuscular mycorrhizal fungi had different effects on the extractability of Zn and P fractions (Gholami, 2011; Morovat, 2011). Mycorrhizal symbiosis increased absolute amounts of Zn carbonate and organic forms and decreased extractability of Mn oxides and residual forms of Zn in the rhizosphere of maize (Gholami, 2011). Mycorrhizal symbiosis decreased P chemical forms bound to iron (Fe-P), but increased calcium phosphate hydroxyapatite in the rhizosphere of sunflower (Morovat, 2011). Maize is an effective host of AM in infertile and drought conditions (Christopher and Tony, 2008) and its root system consists of different root types that are formed during different stages of root development (Hochholdinger, 2009). There is no information in the literature on the characterization of K forms and minerals weathering affected by AMF, PGPR and their co-application treatments under maize cultivation. Therefore, the objective of this study was to evaluate the effects of *Glomus intraradices*, *Pseudomonas fluorescens* (as a PGPR bacterium) and soil drying on different forms of K and changes of clay minerals induced by the treatments in a calcareous soil under maize cultivation.

MATERIALS AND METHODS

Preparation of mycorrhizal and bacterial inocula

Mycorrhizal inoculum was prepared through the trap culture of forage sorghum (*Sorghum biocolor* L.) with spore of *Glomus intraradices*. The fungus was isolated from a non-contaminated area of Anguran mine, Zanjan, Iran (Zarei, 2008). *Glomus intraradices* are abundantly reported in the soils of Iran (Aliasgharzadeh et al., 2001; Zarei et al., 2008; Mehraban et al., 2009). Trap culture medium was composed of autoclaved soil/quartz-sand (<1 mm) (4:1, v/v). At the beginning of the reproductive stage (i. e., 4.5 months after emergence), shoots were harvested and the contents of pot (i. e., colonized roots plus soil possessing fungal spores and mycelia) were transferred to polyethylene bags and kept at 4°C. Simultaneously, some pots were kept without any spore inoculation for preserving of microbial association and used as control treatments. The potential of inoculum (spore numbers of 12 g^{-1} substrates and root colonization of 80%) was measured for spore extraction and counting, and evaluation of root colonization (Zarei et al., 2008). The bacterium used in the present experiment was *Pseudomonas fluorescens* and provided by soil biology and biotechnology laboratory of College of Agriculture and Natural Resources of Tehran University, Karaj, Iran. The seeds were inoculated with 1mL fresh and active suspension of bacterium (population of 1×10^8 colony-forming units (CFU) per milliliter). The plant growth promoting activities of this strain were studied by Malekzade (2010) and Malekzade et al. (2010). Their results showed that bacterium had a high ability to dissolve poorly soluble organic and inorganic phosphate compounds, to produce siderophores, indole acetic acid (IAA), and 1-aminocyclopropane-1-carboxylate (ACC)-deaminase enzyme (Malekzade, 2010; Malekzade et al., 2010).

Soil preparation and analysis

A non-sterile composite soil sample was collected from depth of 0-30 cm soil surface of Agriculture Research Station of Shiraz University, Shiraz, Iran (*fine*, *mixed*, *mesic*, *Calcixerollic Xerochrept*). The samples were air-dried and passed through a 2 mm sieve. Some physical and chemical properties of studied soil are presented in Table 1. Particle size analysis was determined by the hydrometer method (Gee and Bauder, 1986). Soluble and exchangeable K was extracted by 1 N NH_4OAc, non-exchangeable K was determined by the 1 M boiling HNO_3 method and total K by HF digestion (Helmke and Sparks, 1996). Soil pH was determined in a saturated paste using a glass electrode (Thomas, 1996). Cation exchange capacity (CEC) was measured by the saturation method (Summer and Miller, 1996), soil organic matter by oxidation with chromic acid and then titration with ferrous ammonium sulfate (Nelson and Sommers, 1996). Field capacity (FC) and permanent wilting point (PWP) were measured by the pressure plate.

Table 1. Chemical and physical properties of the soil sample

pH	Sand	Silt	Clay	CEC*	OM	TN	OP	Fe-DTPA	Zn-DTPA	Mn-DTPA	Cu-DTPA	NH_4OAc-K	HNO_3–K	HF-K
	……%.....			$cmol_+ kg^{-1}$	%	%	……	mg kg^{-1}				…… mg kg^{-1}		
7.4	20	60	20	18.5	2.1	o.1	18.1	3.8	0.5	8.7	1.4	350	650	890

* CEC, Cationexchange capacity; TN: Total nitrogen; OP:Olsen-Phosphorus; OM, Organic matter

Determination of soil dryinglevels

For determination of drought stress levels, moisture content of pots containing 3 kg of the soil was brought to field capacity (FC) (FC and permanent wilting point were measured by the pressure plate before) and the total weight was recorded. Pots were weighed daily at the specified time for 15 days. In addition, the daily moisture reduction was recorded by using the following formula and the mentioned soil drying (2 days equivalent to 100% moisture, 4 days equivalent to75% moisture, 6 days equivalent to 50% moisture and 8 days equivalent to 25% moisture content) was obtained (Sepaskhah and Yarami, 2009).
Daily Moisture reduction is Eq 1:

$$\frac{\theta_{FC} - \theta_{specific\ day}}{\theta_{PWP} - \theta_{FC}} \quad (1)$$

where is FC: Field Capacity, PWP: Permanent Wilting Point, θ: Moisture content.

Then, soil moisture retention curve was plotted through moisture contents obtained during the 15 days. (Moisture content on the vertical axis and time on the horizontal axis were shown). Afterwards, by using this curve, four irrigation intervals or soil drying intervals of 2, 4, 6 and 8 days were determined.

Greenhouse experiment

A factorial experiment with a completely randomized design was conducted under greenhouse conditions, using the pot culture of maize (*Zea mays* L. var. Single cross 704) in a non-sterile soil, described previously. The factors consisted of arbuscular mycorrhizal (AM) fungus at two levels: G_0 (not inoculated with fungus) and G_1 (inoculated with *Glomus intraradices*), bacteria at two levels B_0 (not inoculated with bacterium) and B_1 (inoculated with *Pseudomonas fluorescence*) and soil drying levels or four irrigation intervals of 2 (S_0), 4 (S_1), 6(S_2) and 8(S_3) days. Each treatment was replicated three times. Each pot was filled with 3 kg soil. All pots received a uniform application of 150 mg N kg^{-1} of soil as urea, and Fe, Zn, Cu, and Mn at a rate of 5, 10, 2.5 and 10 mg kg^{-1} of soil as Fe-EDDHA, $ZnSO_4.7H_2O$, $CuSO_4.5H_2O$, $MnSO_4.H_2O$, respectively. All fertilizers were added in liquid form to facilitate distribution. In mycorrhizal treatments, 50g inoculum of AM fungus, *Glomus intraradices*, was spread as a thin layer below the soil surface. Six seeds of maize were planted in each pot. In bacterial treatments, each seed was inoculated with 1mL of bacterial inoculum (1×10^8cfu mL^{-1}). After germination, seedlings were thinned to two uniform plants in each pot. Drought stress was applied after 3 weeks of planting. The temperature during experiment ranged from 15 to 28 ℃, with a 16/8 h light/dark period.

Plant harvesting and analyses

After a growth period of 4 months, plant aerial parts were cut; soil sample in each pot was harvested and samples of fresh roots were taken to assess root colonization rate. The percentage of root colonization by AM fungus using the grid-line intersect method was determined after clearing washed roots in 8% KOH and staining with blue ink (Pelican, Hanover, Germany) lactoglycerol solution (Kormanik and McGraw, 1982). In order to determine different forms of K, different extractants were used: soluble and exchangeable K was extracted by 1 N NH_4OAc, non-exchangeable K by 1 M boiling HNO_3 and total K by HF digestion (Helmke and Sparks, 1996). Finally, extractable K concentrations were measured by using a flame photometer. Thereafter, a mineralogical analysis of the clay fraction of soil samples (from cultivated pots) was performed by using the procedure given by Kittric and Hope (1963) and Jackson (1975). The clay-sized particles were separated using a centrifuge and examined by X-ray diffraction (XRD). Oriented slides were prepared for both K and Mg saturated samples. The Mg saturated samples were solvated with ethylene glycol (EG), while the K-saturated samples were heated at 550°C. Mineralogical changes were investigated with a XRD instrument (Jones et al., 1980) and peak height intensity was used as an indicator showing the relative abundance of minerals. The abundance of minerals is classified by Jones et al. (1980).

Statistical analysis

Data were subjected to analysis of variance (ANOVA) and means were compared by least significant difference (LSD) at 5% level of significance using SAS software (Statistical Analysis Software, v. 9.1).

RESULTS AND DISCUSSION

Root colonization

The root colonization results are shown in Table 2. Root colonization decreased as soil drying levels increased. Plants inoculated with *G. intraradices* (G_1) had higher root colonization value than non mycorrhizal (G_0) treatments. In non mycorrhizal treatments, root colonization varied between 9.0-24.5 percent and in mycorrhizal treatments, root colonization varied between 62-92 percent. In mycorrhizal and non-mycorrhizal treatments, inoculation of plant with bacterium increased root colonization percentage. The maximum root colonization percentage (92%) was in G_1B_1 treatments (Table 2).

The forms of K in the soil

The K forms in the soil after plant harvest are shown in Table 2. Soil drying increased all forms of K in the studied soil. The minimum amounts of K forms were in soil drying of 2 days and the maximum was at soil drying of 2 days. Inoculation of plants with *G. intraradices* increased all forms of K in soil as compared to non mycorrhizal ones. In non mycorrhizal and mycorrhizal treatments, inoculation of plants with *Pseudomonas fluorescence* increased all forms of K in soil. Co-inoculation treatments of plants with AM fungus and bacterium had the maximum amounts of K forms as compared to inoculation of plants with AM fungus or bacterium treatments (Table 2).

Mineral in the soil samples

The minerals observed in the soil after the plants were harvested are shown in Table 3. They were illite, chlorite, smectite, illite-smectite and, illite-chlorite minerals.

In non mycorrhizal treatments, illite, chlorite, illite-chlorite, and illite-smectite minerals and in mycorrhizal treatments, illite, chlorite, smectite, and illite-chlorite minerals were observed. In non mycorrhizal treatments, there were no smectite minerals. Inoculation of plants with bacterium had no effect on the presence of smectite minerals in soils. However, by increasing soil drying levels, the amount of illite-chlorite minerals increased (Table 3).

In mycorrhizal treatments, the quantity of smectite minerals increased as the soil drying levels increased. The maximum amount of smectite minerals was detected in co-inoculation treatments of plants with AM fungus and bacterium. In most mycorrhizal treatments, by increasing smectite minerals, the amount of illite and illite-chlorite minerals decreased (Table 3). For example, the X-ray diffraction (XRD) patterns of $G_0B_0S_0$ (control treatment) and $G_1B_1S_3$ (Please see M&M) were presented in Figs. 1 and 2.

Table 2. The Effects of arbuscular mycorrhizal fungus, bacterium and drought stress on root colonization percentage, soil K concentrations extracted by NH_4OAc, boiling HNO_3 and HF (mg kg^{-1}) after plant harvest

Treatments	Root Colonization (%)	K extractable with NH_4OAc (mg kg^{-1})	K extractable with boiling HNO_3 (mg kg^{-1})	K extractable with HF (mg kg^{-1})
$G_0B_0S_0$	14.3 d◆	293.3 b	260.0 b	6133.3 c
$G_0B_0S_1$	11.6 d	296.7 b	293.3 a,b	6866.7 b,c
$G_0B_0S_2$	11.1 d	300 b	313.3 a,b	7400 a-c
$G_0B_0S_3$	9.1 d	313.3 b	360 a,b	7400 a-c
$G_0B_1S_0$	24.6 d	313.3 b	373.3 a,b	7466.7 a-c
$G_0B_1S_1$	23.3 d	326.7 b	373.3 a,b	7666.7 a-c
$G_0B_1S_2$	19.7 d	326.7 b	380 a,b	7833.3 a-c
$G_0B_1S_3$	17.6 d	330 b	393.3 a,b	7866.7 a-c
$G_1B_0S_0$	83.1 a-c	333.3 b	393.3 a,b	7900 a-c
$G_1B_0S_1$	48.7 a-c	333.3 b	413.3 a,b	7966.7 a-c
$G_1B_0S_2$	68.4 b,c	340 b	420 a,b	8433.3 a,b
$G_1B_0S_3$	62 c	343.3 b	426.7 a,b	8466.7 a,b
$G_1B_1S_0$	92 a	350 b	473.3 a,b	8466.7 a,b
$G_1B_1S_1$	88.3 a,b	363.3 a,b	493.3 a,b	8600 a,b
$G_1B_1S_2$	86.4 a,b	373.3 a,b	553.3 a	8900 a
$G_1B_1S_3$	67.6 b,c	470 a	553.3 a	9266.7 a
Analysis of	variance			
G	***	*	*	**
B	*	NS	NS	*
S	NS	NS	NS	NS
G×B	NS	NS	NS	NS
B×S	NS	NS	NS	NS
G×S	NS	NS	NS	NS
G×B×S	NS	NS	NS	NS

The numbers in each column with a same small letter are not statistically significant at 5% level with LSD test.G_0 (not inoculated with fungus) and G_1 (inoculated with *Glomusintraradices*), B_0 (not inoculated with bacterium) and B_1 (inoculated with *Pseudomonas fluorescence*) and soil drying levels or four irrigation intervals of 2 (S_0), 4 (S_1), 6 (S_2) and 8 (S_3) days. ***, ** and*, significant at 0.1, 1 and 5 percent, respectively. NS: Non Significant.

Table 3. The relative abundance (based onarea under the curve of X-ray diffraction) of clay minerals in the soil samples after harvesting the plant.

Treatments	Illite	Chlorite	Smectite	Illite-Smectite	Illite-Chlorite
$G_0B_0S_0$	++	+++	-	+	-
$G_0B_0S_1$	+++	++	-	-	-
$G_0B_0S_2$	+++	++	-	-	+
$G_0B_0S_3$	+++	+++	-	-	+
$G_0B_1S_0$	+++	++	-	-	+
$G_0B_1S_1$	++	+++	-	-	+
$G_0B_1S_2$	++	++	-	-	++
$G_0B_1S_3$	++	++	-	-	++
$G_1B_0S_0$	+++	+	+	-	+
$G_1B_0S_1$	+	++	+	-	++
$G_1B_0S_2$	++	++	++	-	+
$G_1B_0S_3$	++	++	++	-	-
$G_1B_1S_0$	++	++	++	-	-
$G_1B_1S_1$	++	++	++	-	-
$G_1B_1S_2$	++	-	++	-	++
$G_1B_1S_3$	++	-	+++	-	+

-Negligible (0-3%), + few (3-20%), ++ medium (20-40%) and +++ % High (40-70%). G_0 (not inoculated with fungus), G_1 (*Glomus intraradices*), B_0 (not inoculated with bacterium), B_1 (*Pseudomonas fluorescence*), S_0 ((%100 FC), S_1 (75 FC), S_2 (%50 FC) and S_3 (%25 FC).

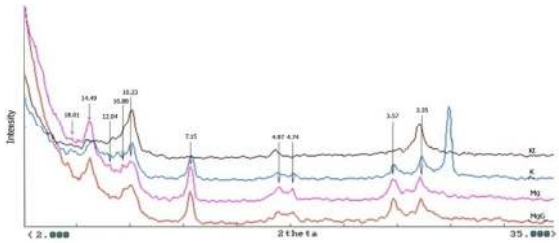

Fig. 1. X-ray diffraction pattern of soil sample $G_0B_0S_0$ (control treatment) after harvesting the plant (Mg: Magnesium saturated sample, Mg-Eg: Mg saturated and ethylene glycol solvated sample, K: Potassium saturated sample, K-550°: K saturated sample heated at 550°C).

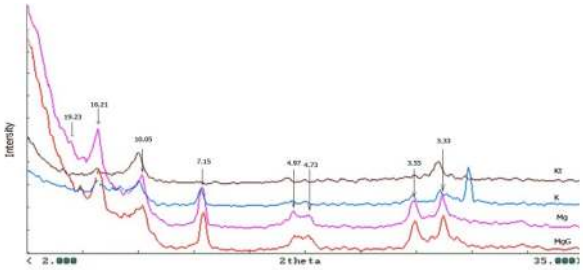

Fig. 2. X-ray diffraction pattern of soil sample $G_1B_1S_3$ (Please see M&M) after harvesting the plant (Mg: Magnesium saturated sample, Mg -Eg: Mg saturated and ethylene glycol solvated sample, K: Potassium saturated sample, K-550: K saturated sample heated at 550°C).

Biological factors

Data showed that the fungus and bacterium affected the root colonization and weathering of minerals and consequently releasing non-exchangeable K. Smectite minerals were also observed in fungus treatments which is probably due to its secretions and release of K. It is believed that weathering of minerals is performed by organic acids released by organisms (Wang et al., 2000; Sugumaran and Janartanan, 2007). Organic acids dissolve minerals by two mechanisms: the production of protons and the ligand forming with the elements in minerals. On the other hand, organic acids increase the dissolution rate of minerals by forming complexes with soluble products (Ulman and Welch, 2002). Moreover, oxidation of glucose to organic acids is the main mechanism by which microorganisms can increase the dissolution of feldspars under the soil's natural pH conditions (Vandevivere et al., 1994). Other mechanisms such as the formation of soluble complexes of organic ligands, bio-stable polymers such as the secretion of non-soluble components, and the mechanical forces associated with the direct physical contact between cells and mineral particles have been proposed to enhance K release ((Lian et al., 2008; Basak and Biswas, 2009). In several studies, the role of plants inoculated with mycorrhizal fungi has been discussed. Yuan et al. (2004) examined the release of K from clay minerals by ectomycorrhiza fungi and young eucaluptus seedling root. Their results showed that in the presence of mycorrhiza, K uptake was significantly different from the control. Inoculation of soybean roots with AMF accelerated the weathering of biotites and phologopite (Mojallali and Weed, 1978).

Mixed minerals were higher in the soils treated with bacterium and increased soil drying levels. It seems that bacteria enhance the transformation of mica and chlorite into mixed minerals. Basak and Biswas (2009) showed the significant release of K from micaceous minerals that had been inoculated with *Bacillus mucilaginosus* bacterial species. X-ray analysis also showed more mica dissolution which was due to inoculation of *Bacillus mucilaginosus*.

The highest amounts of root colonization, NH_4OAc, 1 M boiling HNO_3 and HF extractable K were observed in the co-inoculation treatments of plants with AM fungus and bacterium. A synergistic effect of fungus and bacterium treatments is, therefore, thought to be the main reason. Release of K leads to a simple modification of illite to smectite minerals. Synergistic effects of AMF and bacteria have been shown in other studies (Zarei et al., 2006). Plant roots, also, play an important role in mineral weathering. They deplete the K rhizosphere and thus shift the exchange equilibrium so that the interlayer K is released and the interlayer spaces of the micas are expanded. Hinsinger et al. (1992) indicated that roots were forced to us einterlayer K of minerals to compensate the lack of K in cases where plants received no K from nutrient solution. This action occurs due to the fact that roots are an organ of nutrient absorption. Fageria and Stone (2005) showed that in the rhizosphere of maize, sugars, organic acids (citric and oxalic) and amino acids are secreted and release of non-exchangeable K occurs if K is deficient in solution. Badraoui et al. (1992) studied the growth of Italian ryegrass (*Lolium multiflorum* L.) in pots

containing soils with high mica (illite) and smectite. They concluded that chemical and mineralogical properties of soils greatly affect the mobility of non-exchangeable K in the vicinity of the plant and soils which contain illite. Non-exchangeable K was released. Tributh et al. (1987) studied the effect of K fertilizers on deformation of clay minerals in soils under *cultivation* on ryegrass plants.-ray diffraction analysis of soil samples showed that cultivation without the use of K can lead to a significant reduction in illite clay minerals and can increase the amount of smectite and mixed layer illite-smectite.

Studies have shown that both soluble and exchangeable K are discharged due to the biological effects and absorption by plant roots in the vicinity of the rhizosphere. Reducing the concentration of K in the rhizosphere can explain the release of non-exchangeable K in the root vicinity (Maclean and Watson, 1985). So, mica and illite interlayer K are the main source of K release during the growth period (Mengel, 1985; Goulding, 1987).

Environmental factor

Root colonization decreased by increasing soil drying (Table 2). This is in agreement with Al-Karaki and Al-Raddad (1997). With reduced soil moisture, the quantity and quality of root exudates are changed and this, in turn, influences the germination of spores. Reduced humidity also directly affects the germination of spores (Smith and Read, 2008).

Moreover, data indicated that the release of K leads to a simple modification of illite to smectite minerals through increasing soil drying. In fact, soil drying may allow redistribution of interlayer cations. Since this study was conducted in calcareous soils, calcium ions can compete with K for wedge sites. This process seems to cause the release of K in the soil (Najafighiri, 2010). Two different processes may occur during the soil drying, namely, stabilization of K in wedge exchange sites and its release due to the ductility of clay layers (Scott and Smith, 1968). The outcome depends on both the dominant process and decisive releasing or stabilization process (Olk et al., 1995).

CONCLUSIONS

Glomus intraradices and *Pseudomonas fluorescens* bacterium have a significant effect on root colonization and extractable K. *Glomus intraradices* affects the K extracted by NH_4OAc, HNO_3, and HF digestion and *Pseudomonas fluorescens* affects K extracted by HF digestion. By increasing soil drying levels, extractable K with NH_4OAc, HNO_3 and HF increased. Thus, by increasing drought stress, release of non-exchangeable K to exchangeable K increased.

Moreover, the results represent high values of smectite minerals in the co-inoculation treatments of plants with AM fungus and bacterium. This may be an indication that microbial weathering of illite to smectite minerals has taken place. Transformation of illite to smectite minerals was evident from XRD. In addition to the role of fungus, and bacteria to some extent, it was assumed that transformation was the result of the processes occurring in the rhizosphere of maize which include the release of H^+ and uptake of K by plan troots. The roots deplete K in the rhizosphere and thus shift the exchange equilibrium. This would result in the release of interlayer K and the expansion of interlayer space of illite leading to the transformation of illite and mixed layer illite-chrorite to smectite. Also, when the drought stress increases, release of K leads to a simple modification of illite to smectite minerals. Based on the results obtained in this study, it may be concluded that the use of biofertilizers is very effective in weathering the minerals under soil drying conditions.

Therefore, it is expected that by the exit of interlayer K of minerals to supply the K needed for the plants, changes will be expected in their mineralogy. Further investigation is needed to fully understand the changes in maize rhizosphere and to determine the contribution of different processes of K release by micaceous minerals.

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اثرات قارچ میکوریز آربسکولار، باکتری محرک رشد گیاه و تنش خشکی بر روی شکل‌های مختلف پتاسیم و تغییرات کانی‌های رسی در یک خاک آهکی خاک زیر کشت ذرت

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چکیده– آزمایش گلخانه ای با استفاده از آزمون فاکتوریل در قالب طرح کاملا تصادفی به منظور بررسی اثرات قارچ گلوموس اینترارادایسز، باکتری سودوموناس فلورسنس و تنش خشکی بر روی شکل‌های مختلف پتاسیم و تغییرات کانی‌های رسی در یک خاک آهکی خاک زیر کشت ذرت انجام شد. تیمارها شامل قارچ میکوریز آربسکولار در دو سطح G_0 (تلقیح نشده با قارچ) و G_1 (گلوموس اینترارادایسز)، باکتری سودوموناس فلورسنس در دو سطح B_0 (تلقیح نشده با باکتری) و B_1 (سودوموناس فلورسنس)، تنش خشکی در چهار سطح S_0 (بدون تنش)، S_1 (تنش FC ۷۵٪)، S_2(تنش FC ۵۰٪) و S_3(تنش FC ۲۵٪) بود. با افزایش تنش خشکی، همه شکلهای پتاسیم افزایش و درصدکلنیزاسیون ریشه کاهش یافت. مایه زنی میکروبی درصد کلنیزاسیون ریشه و همه شکلهای پتاسیم خاک را در مقایسه با تیمارهای مایه زنی نشده افزایش داد. با این وجود اثرات مایه زنی انفرادی گیاه با باکتری کمتر بود. بیشترین درصد کلنیزاسیون ریشه و مقدار شکلهای مختلف پتاسیم در تیمارهای مایه زنی گیاه با هر دو قارچ و باکتری در مقایسه با تیمارهای مایه زنی انفرادی مشاهده شد. با افزایش تنش خشکی مقدار کانی های ایلایت-کلریت افزایش یافت. با افزایش سطوح تنش خشکی، در تیمارهای غیر میکوریزی کانی های اسمکتیت مشاهده نگردید در حالیکه در تیمارهای میکوریزی مقدار این کانی ها افزایش یافت. بطور کلی نتایج نشان داد که کودهای زیستی و تنش خشکی در هوادیدگی و انحلال کانیها و رهاسازی پتاسیم موثر هستند.