Australian Journal of Crop Science AJCS
AJCS 5(5):554-561 (2011) ISSN:1835-2707

Effects of elemental sulfur, phosphorus, micronutrients and *Paracoccus versutus* on nutrient availability of calcareous soils

Abdou A. Soaud[1], Fareed H. Al Darwish[2], Maher E. Saleh[3], Khaled A. El-Tarabily[4], M. Sofian-Azirun[5] and M. Motior Rahman[5*]

[1]Department of Soil Science, Faculty of Science, Cairo University, Egypt
[2]Aridland Agriculture, College of Food Systems, United Arab Emirates University, Al-Ain, 17551, United Arab Emirates
[3]Department of Microbiology, Faculty of Science, University of Ain Shams, Cairo, 11566 Egypt
[4]Department of Biology, Faculty of Science, United Arab Emirates University, Al-Ain, 17551, United Arab Emirates
[5]Institute of Biological Sciences, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia

*Corresponding author: mmotiorrahman@gmail.com; mmotiorrahman@um.edu.my

Abstract

This study was carried out in the laboratory to investigate the effects of elemental sulfur (S^0), *Paracoccus versutus (Pv)*, phosphorus (P) and micronutrients (DTPA extractable Fe+Mn+Zn) both singly and combined on nutrient availability of calcareous soils. Soils were collected from Al Semaih, Al Dhahrah and Melaiha in United Arab Emirates (UAE) and all soils were incubated at 40 ± 2^0C for 32, 64, 96 and 128 days. Soil pH dropped and S concentration increased significantly with the addition of S^0 alone or in combination with *Pv*, P and micronutrients in all types of soils. Elemental S application considerably increased the electrical conductivity (EC) of Al Semaih and Melaiha soils but reduced EC in Al Dhahrah soils at 128 days after incubation (DAI). Phosphorus availability was higher and prolonged with the application of S^0 along with P. Zinc (Zn) and manganese (Mn) availability did not increase with the individual application of S^0 or P. Inoculation of *Pv* influenced S and P availability but had no effect on iron (Fe), Mn and Zn. The study suggests that S^0 is an effective agent for the amendment of sandy calcareous soils. Application of S^0 accompanied with *Pv*, P and micronutrients are essential for nutrient availability in calcareous soils.

Keywords: Calcareous soil, Elemental Sulfur, Micronutrients.
Abbreviations: DAI-days after incubation, EC-electrical conductivity, S^0-elemental sulfur, Fe-iron, Mn-manganese, N-nitrogen, *Pv-Paracoccus versutus*, P-phosphorus, S-sulfur, Zn-zinc, UAE-United Arab Emirates.

Introduction

S deficiency is a very common phenomenon in Asia, North America and Western Europe. Elemental S is widely used in Canada, New Zealand, Australia and China to alleviate S deficiency (Slaton et al., 2001; Hu et al., 2003). Most of the agricultural land of United Arab Emirates is calcareous soil that contains relatively high amounts of $CaCO_3$ and extremely poor organic matter resulting in high pH (Abdou, 2006; Khaled et al., 2006). Poor availability of nutrients rather than low nutrient content is one of the major factors for the widespread occurrence of plant nutrient deficiency in calcareous soils. The nutrient uptake of plant is governed by numerous soil factors. Among them, high soil pH and $CaCO_3$ contents are predominantly responsible for low availability of plant nutrients (Kaya et al., 2009). Under unfavorable soil conditions with high pH and $CaCO_3$, only with application of N, P and K fertilizer can't resolve the nutrient deficiency. The nutrient availability of soils can be increased with the application of S^0. Thus, there is a growing interest in S applications to improve availability of nutrients and overcome nutrient deficiencies in both alkaline and calcareous soils (Dawood et al., 1985; Neilsen et al., 1993). Because of the high cost and adverse effects of commercial fertilizers especially N, P and K fertilizer, use of natural sources, micronutrients and S^0 may be used as a nutrient and soil acidifier (Neilsen et al., 1993) and S^0 fertilizer has recently gained importance in agricultural production (Bender et al., 1998; Erdal and Tarakcıoglu, 2000; Atilgan et al., 2008). An individual application of S^0 or combined with Fe dropped soil pH in calcareous soil (Abbaspour et al., 2004) but application of S^0 combined with N fertilizer significantly increased the availability of micronutrients (Erdal et al., 2004). Sulfur is a constituent of the amino acids cysteine and methionine and part of proteins that plays an important role in the synthesis of vitamins and chlorophyll in the cell (Marschner, 1995; Kacar and Katkat, 2007). As a result of S deficiency, plants show retarded growth (Motior et al., 2011) and reduction in yield and quality. The efficacy of S^0 to satisfy the S demand of crops depends, however, on speed and magnitude of its oxidation to S, which is taken up by plants (Yang et al., 2010). The effectiveness of S^0 is governed by its oxidation rate, which is primarily a microbiological function. Thus physical factors such as soil temperature and moisture play an important role in regulating S oxidation (Janzen and Bettany, 1987). The oxidation of S

Table 1. Physicochemical properties of studied soil

Soil Property	Al Semaih	Al Dhahrah	Melaiha
Texture			
Sand (%)	99.73	86.62	95.00
Silt + Clay (%)	0.27	13.38	5.00
Total $CaCO_3$ (%)	68.17	23.65	38.98
Active $CaCO_3$ (%)	12.50	0.00	3.50
Organic Matter (%)	0.14	0.32	0.17
EC, dS m^{-1}	8.85	10.01	2.50
pH (1:2.5)	8.48	8.22	8.60
Soluble cations (meq L^{-1}):			
Ca	28.60	32.40	9.20
Mg	15.80	32.60	5.40
Na	29.60	24.66	14.80
K	0.91	0.65	0.10
Soluble anions (meq L^{-1}):			
Cl	63.20	85.00	16.60
HCO_3	1.30	3.20	1.70
SO_4	46.04	28.96	5.67
Olsen P, mg kg^{-1}	0.36	1.31	0.20
DTPA extractable Micronutrients (mg kg^{-1} soil):			
Fe	2.78	2.80	1.44
Mn	4.10	1.76	1.78
Zn	1.08	3.20	0.30
Cu	0.36	0.30	0.13

into H_2SO_4 is especially beneficial for alkaline soils for increasing nutrient availability by reducing pH (Nielsen et al., 1993). Elemental S is the standard acidulant applied to soil for pH reduction (Slaton et al., 1999). The reactivity of $CaCO_3$ is considered an important property of soil which influences soil chemical and rhizosphere processes (Loeppert and Suarez, 1996) and management of soil pH for optimum nutrient availability has to be considered for quality crop production (Slatoon et al., 1999). Application of S^0 increased the availability of P and micronutrients to correct their deficiencies in alkaline and calcareous soils (Hilal and Abd-Elfattah, 1987) and increased the chemically available P from native soil apatite or added rock phosphate (Garcia and Carloni, 1977), while in others it increased available P only when P-fertilizer was added to the soil but soil P was not affected (Gupta and Mehla, 1980). Application of S^0 has been suggested as an option with regard to reclamation of alkaline solonetzic soils (Rupela and Tauro, 1973). The acidity produced during S^0 oxidation increases the availability of nutrients such as P, Mn, Mg, Ca, and SO_4 in soils (Lindemann et al., 1991). The oxidation of S^0 in calcareous soils is affected by several factors such as particle size of S^0, soil moisture, temperature, pH, nutrient status and microbial activity of the soils. Sulfur oxidation is the most rapid under low soil pH conditions (Havlin et al., 1999). The main effect of S^0 application to soil, particularly calcareous soils and subsequent S oxidation is the reduction in soil pH (Shadfan and Hussen, 1985). Elemental S application increased the Zn and Cd solubilization in soil and increased their uptake by plants (Kayser et al., 2001). The organic P reduced while inorganic P increased from soil acidification with the application of S^0, resulting in the availability of K, P, Fe, Zn, Mn, and Cu (Chouliaras and Tsadilas, 1996). Iron and Mn availability is directly associated with the status of soil pH. Alkaline soil conditions can render Fe unavailable to plant uptake. Zinc deficiency can occur on alkaline soils and sandy soils with poor organic matter content. High levels of P coupled with low levels of Zn in soil may induce Zn deficiency. The application of S often increases the availability of P in neutral or basic soils (Carl and Roger, 1996) and adequate supplies of other plant nutrients tend to increase the absorption of P in soils. Therefore, the present work was undertaken to investigate the effects of S^0, P, *Pv* and DTPA extractable micronutrients on nutrient availability in soils from three regions which represents major areas in UAE.

Materials and methods

Experimental design

The experiments were carried out in the laboratory of College of Food Systems, United Arab Emirates University. Sandy calcareous soil was collected from three regions of UAE such as Al Semaih, Abu Dhabi (24° 28'0"N, 54°22'0"E), Al Dhaharh, Al Ain (24°12′27″N 55°44′41″E) and Melaiha, Al Zaid (25°21′44″N 55°23′28″E) at a depth of 0-25 cm to represent the major areas of calcareous soils in UAE. An individual experiment was conducted with each type of soils. The treatments such as control, S^0 (particle size < 150 µm) at the rate of 1000 kg/ha, *Pv*, S^0+*Pv*, phosphorus (P), S^0+P, S^0+P+*Pv*, DTPA extractable Fe+Mn+Zn, S^0+DTPA extractable Fe+Mn+Zn, and S^0+*Pv*+DTPA extractable Fe+Mn+Zn were tested under complete randomized design with three replications.

Management practices

A part of collected soil sample was air dried and sieved through 1-mm stainless steel sieve and analyzed for physicochemical properties (Table 1). Air dried 100 g soil samples were placed into 200-ml plastic jars and incubated at constant temperature (40±2^{0}C) for 32, 64, 96 and 128 days to determine pH, soil salinity and nutrients availability of S, P, Fe, Mn and Zn. Organic matter in tested soils ranged from 0.14-0.32% (Table 1). Elemental S was added at the rate of 444 mg/kg of soil corresponding to 1000 kg S^0/ha and thoroughly mixed with soil and transferred into 200-mL plastic jars. Phosphorus was added to soil at the rate of 5 ml solution containing 0.0418 g P_2O_5/100 g of soil corresponding

Table 2. Soil EC (dSm^{-1}) status in incubated soil as affected by elemental sulfur, *Paracoccus versutus*, phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after incubation				Days after incubation				Days after incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	10.43	13.44	9.10	8.96	12.38	10.38	9.78	9.11	5.15	4.37	4.16	2.91
S^0	9.22	10.27	9.04	8.93	12.67	8.75	8.71	7.80	3.55	3.27	2.43	2.26
Pv	10.53	11.05	9.51	8.85	10.93	8.73	7.58	7.53	3.09	3.28	2.31	2.30
S^0+*Pv*	9.56	11.82	8.93	8.59	11.70	10.46	9.75	9.50	5.92	4.62	4.40	3.92
P	10.57	12.20	9.85	9.66	11.03	9.10	8.81	7.98	3.74	3.29	2.60	2.59
S^0+P	11.25	12.34	11.20	9.99	13.77	10.90	9.96	9.64	4.93	4.55	4.34	4.19
S^0+P+*Pv*	10.74	12.55	10.27	10.06	14.34	10.79	9.53	9.00	6.09	5.35	5.06	4.40
Fe+Mn+Zn	10.41	11.02	10.56	7.27	12.18	10.85	8.68	8.66	3.50	2.97	2.70	2.33
S^0+Fe+Mn+Zn	11.52	11.57	10.92	10.44	13.10	10.51	9.79	9.58	5.62	4.72	4.39	3.87
S^0+*Pv*+Fe+Mn+Zn	11.91	12.46	10.39	10.07	11.99	10.12	9.88	9.65	5.97	4.84	4.83	4.33
LSD 0.05	2.18	2.25	1.88	0.51	1.54	2.47	3.22	0.83	0.70	1.64	0.71	0.45

Table 3. Soil pH in incubated soil as affected by elemental sulfur, *Paracoccus versutus*, phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after Incubation				Days after Incubation				Days after Incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	7.94	8.14	8.29	8.36	8.03	7.89	8.00	8.29	8.17	8.18	8.29	8.41
S^0	7.65	7.88	8.04	8.28	7.23	7.47	7.59	7.85	7.87	7.90	7.95	7.99
Pv	7.92	8.15	8.30	8.24	7.89	8.06	8.19	8.36	8.23	8.24	8.36	8.53
S^0+*Pv*	7.38	7.86	8.15	8.21	7.30	7.23	7.41	7.72	7.75	7.83	7.88	7.98
P	7.84	8.13	8.36	8.48	7.70	7.74	7.89	8.20	8.27	8.31	8.35	8.62
S^0+P	7.39	7.75	8.24	8.58	7.07	7.19	7.33	7.63	7.70	7.73	7.91	7.97
S^0+P+*Pv*	6.97	7.71	8.11	8.39	6.91	7.07	7.28	7.48	7.47	7.89	7.82	7.79
Fe+Mn+Zn	7.92	8.11	8.39	8.55	7.94	8.08	8.08	8.36	8.25	8.28	8.33	8.57
S^0+Fe+Mn+Zn	7.50	7.83	8.07	8.33	7.29	7.34	7.51	7.79	7.85	7.93	7.96	8.03
S^0+*Pv*+Fe+Mn+Zn	7.31	7.77	7.99	8.25	7.32	7.32	7.51	7.57	7.70	7.92	7.95	8.03
LSD 0.05	0.08	0.08	0.10	0.06	0.09	0.19	0.12	0.13	0.11	0.07	0.08	0.07

to 150 kg P_2O_5/ha in the form of KH_2PO_4. Iron, Mn and Zn were added to soils at the rate of 5 ml solution containing 0.752, 0.543 and 0.627 mg Fe, Mn and Zn, corresponding to 30.0, 10.0 and 10.0 kg EDTA-Fe (6.0 % Fe), EDTA-Mn (13.0 % Mn) and EDTA-Zn (15.0 % Zn) /ha, respectively. The soil samples were saturated with distilled water in the presence and or absence of 5 ml *Pv* as per treatment schedule. Local sulfur-oxidizing bacteria *Pv* (CBS 114155) was used which was previously isolated from the western regions of the UAE (Khaled et al., 2006).The populations of sulfur-oxidized bacteria were used as colony forming units of per ml (cfu/ml) 73.16 x 10^4 (SE±4.75).

Soil analysis

Soils were saturated and incubated at 40±2^{0}C and dried for 4 days and then re-saturated again with distilled water. This process of saturation-drying-saturation is called wetting and drying cycle (W/D). the wetting and drying cycles were repeated at regular 4 days interval. The soil samples were withdrawn at 32, 64, 96, and 128 DAI from each treatment and thereafter crushed and sieved through 1-mm screen. Dried soil samples were crushed and the soil pH, EC, available S, P and micronutrients were determined. Soil pH was determined in soil: water suspensions (1:2.5), as an indicator for S oxidation to H_2SO_4. The pH was measured using a combined pH meter model 900A. In the H_2O-saturation extracts, EC was measured as an indicator for dissolution of $CaCO_3$ by the H_2SO_4 produced. EC measurements were carried out using Orion model 120 microprocessor conductivity meters. Available SO_4-S, as an indicator of S oxidation, was measured using inductive coupled plasma emission spectrophotometer (ICP), Varian model Vista MPX. Available P was extracted using 0.05M (pH 8.5) $NaHCO_3$ solution using soil: solution ratio 1:20 (Kuo, 1996) and determined by spectrophotometer (Murphy and Riley, 1962). In the DTPA-extracts, available Fe, Mn and Zn were determined as a measure of S oxidation effects on nutrient availability using ICP.

Statistical analysis

Statistical analysis was carried out by one-way ANOVA using general linear model to evaluate significant differences between means at 95% level of confidence. It was performed using the Statistical Analysis System (SAS, 2003). Following the differences among treatment means were determined using the Fisher's Protected least significant differences (LSD) comparison method P = 0.05.

Results

Soil salinity in calcareous soils

Initial EC of tested soils were 8.85, 10.01 and 2.50 in Al Semaih, Al Dhahrah and Melaiha, respectively (Table 1). Soil EC was significantly influenced by the various treatments

Table 4. Sulfur concentration (meq l^{-1}) in incubated soil as affected by elemental sulfur, *Paracoccus versutus*, phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after Incubation				Days after Incubation				Days after Incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	233.2	167.4	175.3	155.9	130.1	111.9	92.5	87.7	31.5	22.3	19.5	15.4
S^0	267.7	238.0	192.5	187.6	264.5	246.7	206.0	198.8	191.7	176.0	166.3	156.1
Pv	252.3	231.1	196.1	165.2	142.0	125.2	98.4	91.5	33.8	23.9	22.2	19.7
S^0+*Pv*	351.1	297.8	203.1	181.0	272.8	244.1	238.3	203.7	306.0	185.4	153.5	145.5
P	255.5	240.8	189.1	155.3	168.2	120.6	79.4	93.8	33.4	22.4	21.7	20.6
S^0+P	351.6	288.5	223.2	178.2	302.8	264.3	238.6	222.1	194.3	201.4	178.7	148.6
S^0+P+*Pv*	429.7	327.5	255.6	214.4	376.3	289.5	243.9	232.5	268.4	208.3	192.1	165.7
Fe+Mn+Zn	214.8	238.7	166.2	157.6	153.7	129.2	77.3	66.4	38.7	29.7	25.9	22.2
S^0+Fe+Mn+Zn	287.5	275.7	234.7	207.2	290.7	232.6	229.5	193.1	219.1	172.1	171.1	136.7
S^0+*Pv*+Fe+Mn+Zn	383.9	313.3	258.1	196.9	278.8	183.2	241.7	198.7	326.0	189.0	176.8	142.2
LSD 0.05	36.6	34.9	30.9	18.1	51.2	84.7	38.5	36.1	37.3	16.9	13.1	11.1

Table 5. Phosphorus (mg/kg) concentration in incubated soil as affected by elemental sulfur, *Paracoccus versutus,* phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after Incubation				Days after Incubation				Days after Incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	33.0	14.4	12.9	3.3	75.3	52.3	46.8	25.4	17.1	5.4	4.8	3.5
S^0	38.9	23.1	13.1	2.2	58.2	47.5	44.4	18.4	20.5	5.9	4.1	3.4
Pv	26.1	10.0	9.7	3.3	66.4	48.5	45.5	21.3	18.5	5.0	4.7	3.2
S^0+*Pv*	25.3	8.8	7.5	2.4	59.5	38.4	26.8	15.3	18.9	5.0	4.6	4.1
P	295.5	84.7	58.0	30.0	297.7	117.0	104.0	92.5	334.4	37.5	34.8	32.0
S^0+P	319.9	61.3	48.2	31.2	291.5	156.0	154.1	65.7	348.2	72.0	30.6	28.7
S^0+P+*Pv*	334.4	77.5	75.7	28.6	267.1	132.5	123.8	68.3	342.1	56.9	45.2	37.5
Fe+Mn+Zn	27.9	16.0	9.2	3.2	77.7	46.5	38.6	21.4	17.6	7.7	5.4	4.3
S^0+Fe+Mn+Zn	27.2	8.5	8.4	2.4	67.9	32.6	30.1	14.3	21.3	4.7	4.6	3.0
S^0+*Pv*+Fe+Mn+Zn	28.7	9.2	8.2	2.1	67.4	39.9	33.4	12.1	68.0	6.1	4.6	3.0
LSD 0.05	17.4	3.9	8.3	2.7	28.5	15.1	22.6	6.3	52.8	9.9	6.1	5.1

in all soils (Table 2). In Al Semaih soils, EC reached peak at 64 DAI averaged over the treatments and declined over time in all treatments. Soil EC considerably dropped by addition of S^0+*Pv* and micronutrients at 96 DAI and onwards. In Al Dhahrah soils, EC significantly dropped with the application of S^0 and *Pv* at 64 DAI and but in other treatments reducing trend was observed from 96 DAI and onwards. In Melaiha soils, EC reached peak at 32 DAI and thereafter declined over time regardless of treatments but it was higher than the initial status. Soil EC dropped significantly from the initial status with application of S^0 and *Pv* at 96 DAI and onwards. In Al Daharah soils, the reduction rate of EC was relatively higher than Al Semaih and Melaiha soils.

Soil pH in calcareous soils

Soil pH was significantly affected by the treatments in all types of soils. In Al Semaih soils, pH dropped 0.54 to 1.51 units from the initial pH of 8.48 at 32 DAI (Table 1). A sharp decline (0.83 to 1.51 units) was noticed with the application of S^0 alone or combined with *Pv*, P and micronutrients at 32 DAI and thereafter slowly increased over time (Table 3). Phosphorus singly or combined with S^0 and *Pv* failed to drop soil pH at 128 DAI. In Al Dhahrah soils, the reducing trend of pH was observed up to 64 DAI from the initial pH. Soil pH dropped significantly by the combined effect of S^0+*Pv*+P followed by S^0+P at 32 DAI and thereafter rose slowly but soil pH increased rapidly over time with the application of *Pv*, P and micronutrient treatments in all types of soils (Table 3). Single application of *Pv* and micronutrients could not drop soil pH at 128 DAI. In Melaiha soils, pH dropped at 32 DAI and thereafter gradually rose over time in all treatments. Soil pH reducing rate was conspicuous with the application of S^0 alone or combined with *Pv*, P and micronutrients.

Concentration of S in calcareous soils

Sulfur concentration significantly increased in all treatments throughout the incubation period in all tested soils. The highest concentration of S was recorded from the combined effect of S^0, P and *Pv* in Al Semaih and Al Dhahrah soils while in Melaiha soils, the highest concentration of S was obtained from application of micronutrients along with S^0 and *Pv* followed by S^0+*Pv* at 32 DAI and thereafter declined gradually over time (Table 4). The wetting and drying cycles led to increasing S concentration in control and S-untreated soils too but their reducing rate was remarkably lower than S^0 treated soils. In all tested soils, S^0 treated soils either alone or in combined with P, *Pv* or micronutrients obtained higher concentration of S, regardless of incubation period and declined gradually over time.

Concentration of P in calcareous soils

The P concentration influenced with the application of P along with S^0 and *Pv*. Phosphorus concentration was remarkably higher in all tested soils compared to initial status

Table 6. Iron (mg/kg) concentration in incubated soil as affected by elemental sulfur, *Paracoccus versutus,* phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after Incubation				Days after Incubation				Days after Incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	2.03	2.1	2.07	1.35	3.16	2.97	2.70	1.89	1.22	1.19	1.00	0.91
S^0	1.86	1.95	1.8	1.38	2.64	3.00	2.29	1.67	1.31	1.2	1.09	1.05
Pv	1.98	2.06	1.85	1.5	3.03	3.08	2.85	1.97	1.34	1.25	1.09	0.97
S^0+*Pv*	1.80	2.04	1.75	1.51	2.76	2.85	2.36	1.56	1.37	1.32	1.09	1.03
P	1.65	2.00	1.85	1.46	2.19	2.73	2.59	1.86	1.44	1.4	1.13	1.11
S^0+P	1.56	1.99	1.77	1.23	2.41	2.55	2.39	1.38	1.43	1.24	1.24	0.95
S^0+P+*Pv*	1.36	2.15	1.92	1.27	2.34	2.53	2.18	1.43	1.34	1.22	1.18	1
Fe+Mn+Zn	4.18	3.83	3.14	1.91	4.87	4.83	4.45	3.22	3.05	3.02	2.38	1.79
S^0+Fe+Mn+Zn	4.27	3.72	3.09	2.10	4.69	4.67	4.45	3.05	2.83	2.62	2.36	2.07
S^0+*Pv*+Fe+Mn+Zn	4.34	3.62	3.04	1.77	4.27	4.15	3.85	3.03	3.22	2.24	2.15	1.99
LSD 0.05	0.52	0.37	0.21	0.35	0.66	0.86	0.43	0.29	0.14	0.56	0.37	0.15

Table 7. Zinc concentration in incubated soil as affected by elemental sulfur, *Paracoccus versutus*, phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after Incubation				Days after Incubation				Days after Incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	0.80	0.52	0.62	0.61	3.07	1.52	1.97	1.77	0.23	0.19	0.18	0.34
S^0	0.82	0.62	0.68	0.71	2.36	2.65	2.13	1.93	0.21	0.19	0.17	0.21
Pv	0.91	0.56	0.55	0.96	2.39	2.47	2.18	1.85	0.20	0.20	0.17	0.21
S^0+*Pv*	0.98	0.85	0.63	1.01	2.39	2.51	2.33	1.85	0.21	0.20	0.30	0.20
P	0.68	0.82	0.62	0.73	1.79	2.31	1.94	1.71	0.24	0.24	0.21	0.21
S^0+P	0.56	0.64	0.55	0.46	2.34	1.71	2.46	1.70	0.21	0.23	0.18	0.19
S^0+P+*Pv*	0.55	0.85	0.66	0.49	2.50	1.90	1.79	1.81	0.20	0.19	0.18	0.19
Fe+Mn+Zn	4.26	3.72	2.89	1.83	6.26	5.49	5.29	4.92	3.17	3.90	2.30	2.04
S^0+Fe+Mn+Zn	4.23	3.43	3.01	2.35	7.50	7.12	6.15	5.14	3.21	3.14	2.60	2.42
S^0+*Pv*+Fe+Mn+Zn	4.39	2.99	3.16	1.99	7.52	7.04	5.33	5.28	3.10	2.03	2.28	2.23
LSD 0.05	0.80	0.58	0.64	0.73	0.56	3.25	1.56	0.40	0.21	1.00	0.75	0.27

of P and it might be due to frequent wetting and drying of soils. In Al Semaih soils, P concentration varied from 295.5 to 334.4 mg/kg at 32 DAI and drastically reduced over time by application of P singly or combined with S^0 and *Pv*. In Al Dhahrah and Melaiha soils, P concentration ranged from 267.1 to 297.7 and 334.4 to 348.2 mg/kg, respectively at 32 DAI and thereafter declined sharply over incubation time (Table 5). In Melaiha soils, P concentration was a bit higher than Al Semaih and Al Dharah soils with the application of P combined with S^0 and *Pv* but it was higher in Al Semaih and Al Dhahrah soils with other treatments.

Concentration of Fe in calcareous soils

The concentration of Fe was varied by various treatments in all tested soils (Table 6). Iron concentration was much higher with the application of micronutrients alone or in combined with S^0 or S^0+*Pv* at 32 DAI while other treatments had lower concentration of Fe compared to initial status of Fe in soils. In Al Dhahrah soils, Fe concentration was slightly higher than Al Semaih and Melaiha soils. The higher concentration of Fe was continued up to 128 days with the application of micronutrients individually or in combined with S^0 or micronutrients with S^0 +*Pv* compared to initial status of Fe in soils.

Concentration of Zn in calcareous soils

The concentration of Zn was significantly influenced by the treatments in all types of soils (Table 7). The higher concentration of Zn was obtained by addition of micronutrients singly or in combined with S^0 or S^0+*Pv* at 32 DAI and thereafter declined gradually over time but other treatments showed lower Zn concentration compared to initial status of Zn in all types of soils (Table 1). In Al Dhahrah soils, Zn concentration was appreciably higher than in Al Semaih and Melaiha soils.

***Concentration* of Mn in calcareous soils**

Manganese concentration was also significantly affected by various treatments in all tested soils. In Al Dhahrah soils, Mn concentration was significantly higher than Al Semaih and Melaiha soils. Maximum concentration of Mn was recorded with application of micronutrients combined with S^0+*Pv* followed by micronutrients with S^0 at 32 DAI and continued up to 128 days in Al Semaih soils. In Al Dharah soils, the highest concentration of Mn was obtained from micronutrients along with S^0 followed by micronutrients with S^0+*Pv* at 32 DAI and thereafter sharply declined over incubation time. In Melaiha soils, the highest concentration of Mn was obtained from micronutrients with S^0 followed by micronutrients with S^0+*Pv* but concentration of Mn was lower than the initial status where *Pv,* P and micronutrients were applied (Table 8).

Discussion

In this study, the lowest soil pH values were noticed at 32 DAI in most of the treatments in all soils. Soil pH is an

Table 8. Manganese concentration in incubated soil as affected by elemental sulfur, *Paracoccus versutus*, phosphorus and DTPA extractable Fe+Zn+Mn

Treatment	Al Semaih Soil				Al Dhahrah Soil				Melaiha Soil			
	Days after Incubation				Days after Incubation				Days after Incubation			
	32	64	96	128	32	64	96	128	32	64	96	128
Control	0.40	0.32	0.24	0.23	1.41	1.26	0.84	1.00	1.39	1.00	0.87	0.97
S^0	1.51	3.20	3.44	3.17	3.05	3.26	3.94	4.47	4.04	3.79	3.08	2.89
Pv	0.38	0.52	0.91	3.61	1.74	1.32	1.23	1.09	1.74	0.95	0.89	0.91
S^0+*Pv*	2.63	3.45	4.11	3.76	3.33	3.87	4.53	4.27	5.19	3.81	3.18	3.07
P	0.41	0.37	0.30	0.23	1.33	2.21	1.20	1.21	1.41	1.18	1.10	0.89
S^0+P	0.91	3.42	1.65	0.20	2.30	2.83	3.93	3.57	3.38	3.58	3.14	3.13
S^0+P+*Pv*	2.69	3.16	2.97	1.65	4.05	4.03	3.90	2.82	4.80	4.06	3.35	1.61
Fe+Mn+Zn	3.20	2.63	1.38	0.69	4.60	4.41	3.40	3.40	2.70	2.47	1.36	1.55
S^0+Fe+Mn+Zn	7.95	6.47	5.10	5.05	9.46	8.83	8.44	7.49	7.16	6.74	6.59	6.04
S^0+*Pv*+Fe+Mn+Zn	8.07	7.69	7.28	5.09	8.95	8.40	8.13	7.96	9.31	6.21	5.70	4.10
LSD 0.05	0.66	1.72	1.12	1.82	0.27	2.16	1.30	0.53	0.71	1.98	0.71	0.72

important chemical property that affects nutrient availability and microbial activity. Trace metals such as Fe, Zn and Mn are readily available at lower pH than major nutrients. Soil pH dropped due to the various treatments and soil properties during incubation. Soil pH dropped with the addition of S^0 individually or combined with *Pv* inoculation, P and DTPA extractable micronutrients and also on exposing the soils to the wetting and drying cycles in all treatments. Motior et al., (2011) reported that application of S^0 combined with N fertilizer, soil pH dropped from 9.08 to 7.56 in Al Zaid and Al Semaih soils in UAE. Similar results were also obtained by Lopez-Aguirre et al., (1999) who found that addition of varying levels of S (0, 0.5, 1.0 and 2.0 mg S/g of soil) in alkaline tropical soil, lowered the pH from 8.5 to 7.2 at 45 DAI. In this study, the initial soil pH was 8.22, 8.48 and 8.60 in Al Dhahrah, Al Semaih and Melaiha soils, respectively (Table 1) and with the addition of S^0 individually or combined with *Pv* and P, soil pH dropped 1.13, 1.31 and 1.51 units from the initial pH at Melaiha, Al Dhahrah and Al Semaih, respectively (Table 3). Al Semaih soils is characterized by a high content of $CaCO_3$ (68.17 %) compared with Al Dhahrah (23.65%) and Melaiha (38.98 %) soils. The acidifying effect leading to partial neutralization of $CaCO_3$ can be one of the most important factors for increased nutrient concentration. In the present study all soils are rich in $CaCO_3$ (23.65 to 68.17 %) and with the application of S^0, soil pH dropped proportionately with $CaCO_3$ content in Al Semaih soils followed by Al Dhahrah and Melaiha soils, with the exception that in Melaiha soils, the pH reducing trend fluctuated a bit with $CaCO_3$ content in the soil. Kaplan and Omran (1998) and Erdal et al., (2004) reported that soil pH decreased by 0.11-0.37 unit with the application of S^0, resulting in an increase in nutrient concentration, plant nutrient uptake, chlorophyll concentration, root nodules and dry matter production. Similar results were also reported by Motior et al., (2011) who found that with application of S^0 significantly increased nutrient uptake and dry matter accumulation of maize in sandy calcareous soils of UAE. Soil pH decreased 0.24 units over time when soil was amended by S at rates of 2.5 and 5.0 g S/kg of soil (Cifuentes and Lindemann, 1993; Kaplan and Orman, 1998). Soil inoculated by S-oxidizing bacteria along with higher rates of S application (200g S/kg) significantly dropped soil pH from 7.5 to 3.9 under greenhouse conditions in Kuwaiti soils (Al-Daher et al., 2003). During the oxidation of S, soil pH drops and thus changes unavailable form of most nutrients to available form for plant uptake (Kaya et al., 2009). Erdal et al., (2000) reported that application of S^0 to the soil resulted in 0.11-0.37 unit drop in soil pH. Kaya et al., (2009) showed that soil pH dropped by 0.37-1.08 units after the application of waste containing S compared to a decline in soil pH of 0.37-0.51 units after the application of S^0 alone (Orman and Kaplan, 2000). In Melaiha and Al Semaih soils, EC increased with the application of S^0 singly or in combination, regardless of treatment. In Al Dhahrah soils, EC dropped at 64 DAI (Table 2) and onwards with either a single or combined application of S^0, *Pv* and P. Iron concentration increased similarly with applications of S^0 and S-containing waste depending on the drop in pH (Erdal et al., 2006). Kalbasi et al., (1988) suggested that the application of S changes the pH of the soil or rhizosphere from alkaline to acidic and result in the increase of Fe concentration in plants. The P concentration significantly increased over incubation time in all soils with the single application of P and combined with S^0, *Pv* or S^0+*Pv* in all types of soils. Several studies have indicated previously that application of S^0 in calcareous soils did not affect both native and applied P availability (Falatah, 1998; Lindemann et al., 1991) whilst others have shown that accompaniment of S^0 with P fertilizer applied to calcareous soils increase P availability (Kaplan and Orman, 1998; Saleh, 2001). Saleh (2001) found that application of S^0 in calcareous soil released significant amounts of P from the soil. He also showed that available soil P increased with S or with the wetting and drying cycles of calcareous soils. It has been reported that application of S^0 with *Thiobacillus spp* in Iranian calcareous soils significantly increased the availability of P and the uptake of P in maize plants grown under greenhouse conditions (Besharati and Rastin, 1999). Similarly laboratory incubation of wettable S^0 with calcareous soils at the rate of 120 kg S/ha in the absence and presence of farmyard manure increased the amounts of DTPA-extracted Fe, Mn and Zn (Saleh, 2001). During incubation the total $CaCO_3$ content and SO_4 concentration in soil may affect the oxidation process in S amended soil. Soils inoculated with *Pv* has a significant effect on the concentration of SO_4 and the application of S to non-inoculated soils stimulates the growth of S-oxidizing microorganisms. However, several studies have confirmed the importance of soil inoculation with S-oxidizing bacteria to improve the S^0 oxidation process in calcareous soils (Besharati and Rastin, 1999; Al-Daher et al., 2003). Regardless of incubation time, application of S^0 in soils increased the concentration of available S in both inoculated and non-inoculated tested soils. In all soils, the increase of S concentration in non sulfur-treated samples as a result of the wetting and drying cycles is probably due to the hydrolysis of precipitated sulfate-bearing minerals in these soils. Similar results were obtained by Cifuentes and Lindemann (1993) and they concluded that the application of S into calcareous soils, (2.5 and 5 g S/kg of soil) under laboratory conditions, increased SO_4 by about 246 mg/kg. Variations in Mn behavior, against Fe and Zn, might be related to the solid phase dominance in the tested soils where $CaCO_3$ is considered as the major active solid phase compared to the other reactive phase. The sorption tendency of $CaCO_3$ toward Mn is higher than its affinity toward Fe and Zn, while soil organic matter and Fe hydroxides prefer the sorption and initiate complex formation with Fe and Zn rather than with Mn and Zn, which can also be fixed or initiate complexes with clay minerals (Ford and Sparks, 2000). Because of the closed complexation of Mn with carbonate in the tested soils, the Mn release from the soil could be interpreted to be the result of S application being a soil acidifier. Thus the application of S^0 in calcareous soils enhanced S^0 oxidation consistently and increased Mn availability in the field and did not affect the other micronutrients (Cifuentes and Lindemann, 1993).

Conclusion

Soil properties changed with the application of S^0 and the oxidation of S^0 resulted in direct chemical changes through the lowering of soil pH and an increased S concentration in all soils. Elemental S application considerably increased the EC in Al Semaih and Melaiha soils but reduced EC in Al Dhahrah soils at 128 DAI. Phosphorus availability increased and prolonged with the application of P along with S^0 and *Pv*. Inoculation of soils with *Pv* alone had little effect on nutrient availability but S^0 showed a positive response on the amendment of calcareous soil. Elemental S^0 along with *Pv*, P and DTPA micronutrients played a significant role with regard to nutrient availability in calcareous soils in UAE.

Acknowledgements

This research was supported by a grant from the United Arab Emirates University and Sulfur Project funded by the Japan Cooperation Center, Petroleum (JCCP). The authors would like to thank Prof. Gharib Sayed Ali, Advisor of DVC for Scientific Research and Prof. Abdel Alim Metwally, Dean of College of Food Systems, UAEU and Mr. Koichi Kujirai, Executive Director, JCCP, Prof. Satoshi Matsumoto, Faculty of Bioresources Science, Akita Prefectural University, Japan, for their scientific guidance.

References

Abbaspour A, Baligar VC, Shariatmadari H (2004) Effect of steel converters as iron fertilizer and soil amendment in some calcareous soils. J. Plant Nutr. 27:377-394

Abdou AS (2006) Effect of applied elemental sulfur and sulfur-oxidizing bacteria (Parococcus versutus) into calcareous sandy soils on the availability of native and applied phosphorus and some micronutrients. In:18th World Congress of Soil Science, Philadelphia, Pennsylvania, USA. July 9-15, 2006

Al-Daher R, Al-Baho M, Guerinik K, Al-Mutawa Q, Al-Surrayai T, Sharma N, Al-Rashdan A, Al-Ali A, Al-Kandari R, Iwamatsu E, Yorifuji T, Kadota A, Miyamoto H, Shono T, Kurihara M (2003) Development of an elemental sulfur/sulfur-oxidizing bacteria amendment product for improving desert soil fertility. The Joint State of Kuwait-Japan Symposium in 2003, Samira O, Takashi S (eds.) Kuwait Institute for Scientific Research (KISR) and Japan Cooperation Center, Petroleum (JCCP)

Atilgan A, Coskan A, Alagoz T, Oz H (2008) Application level of chemical and organic fertilizers in the greenhouses of Mediterranean Region and its possible effects, Asian J. Chem. 20:3702-3714

Bender D, Erdal I, Dengiz O, Gurbuz M, Tarakcıoglu C (1998) The effects of different organic materials on some physical properties of clay soil. M. Sefik Yesilsoy International Symposium on Arid Region Soil. 21-24 September, International Agrohydrology Research and Training Center. pp. 506-511, Menemen-Izmir

Besharati H, Rastin NN (1999) Effect of application *Thiobacillus spp*. Inoculants and elemental sulfur on phosphorus availability. Iran J. Soil Water Sci. 13:23-39

Carl JR, Roger E (1996) Nutrient Management for Commercial Fruit and Vegetable Crops in Minnesota, Department of Soil, Water, and Climate Minnesota Extension Service, University of Minnesota

Chouliaras N, Tsadilas C (1996) The influence of acidulation of a calcareous soil by elemental sulfur application on soil properties. Georgike-Ereuna-Nea-Seira. Cited from CAB Abstracts

Cifuentes FR, Lindemann WC (1993) Organic matter stimulation of elemental sulfur oxidation in a calcareous soil. Soil Sci. Soc. Am. J. 57:727-731

Dawood F, Al-Omari SM, Murtatha N (1985) High levels of sulphur affecting availability of some micronutrients in calcareous soils. *In* Proc. Sec. Reg. Conf. on Sulphur and its Usage in Arab Countries, Riyadh, 2-5 March 1985, Saudi Arabia. pp.55-68

Erdal I, Gulser F, Tufenkci S, Saglam M, Karaca S (2000) Influence of sulfur fertilization on corn (*Zea mays* L.) plant growth and phosphorus uptake in a calcareous soil. Yuzuncu Yıl University, J. Natural Appl. Sci. 7(1):37-42

Erdal I, Kepenek K, Kızılgoz I (2004) Effect of foliar iron applications at different growth stages on iron and some nutrient concentrations in strawberry cultivars. Turk. J. Agric. Forest 28:421-427

Erdal I, Kepenek K, Kızılgoz I (2006) Effect of elemental sulphur and sulphur containing waste on the iron nutrition of strawberry plants grown in a calcareous soil. Biol. Agric. Hort. 23:263-272

Erdal I, Tarakcıoglu C (2000) Effect of different organic materials on growth and mineral composition of corn plant (*Zea mays* L.) Ondokuz Mayıs University Faculty of Agriculture, J. Agric. Sci. 15(2):80-85

Falatah AM (1998) Synergistic effects of elemental sulfur and synthetic organic conditioner amendments on selected chemical properties of calcareous soils. Arid Soil Res. Rehabil. 12:73-82

Ford RG, Sparks DL (2000) The nature of Zn. Precipitates formed in the presence of pyrophyllite. Env. Sci. Tech. 34:2479-2483

Garcia ME, Carloni L (1977) The effect of Sulphur on the solubility and forms of phosphorus in soil. Agrochemica 21:163-169

Gupta VR, Mehla IS (1980) Influence of sulphur on the yield and concentration of Cu, Mn, Fe, and Mo in berseem (*Trifolium alexandrium*) grown in two different soils. Plant Soil 56:229-234

Havlin JL, Beaton JD, Tisdal SL, Nelson WL (1999) Soil Fertility and Fertilizers. An Introduction to Nutrient Management. 6th ed. Prentic Hall, New Jersey, USA

Hilal MH, Abd-Elfattah AA (1987) Effect of $CaCO_3$ and clay content of alkali soils on their response to added sulphur. Sulphur Agric. 11:15-17

Hu ZY, Haneklaus S,Wang SP, Xu CK, Cao ZH, Schnug E (2003) Comparison of mineralization and distribution of soil sulphur fractions in the rhizosphere of oilseed rape and rice. Com. Soil Sci. Plant Anal. 34:2243–2257

Janzen HH, Bettany JR (1987) The effect of temperature and water potential on sulphur oxidation in soil. Soil Sci. 144:81-89

Kalbasi M, Filsoof F, Rezai N (1988) Effect of sulphur treatments on yield and uptake of Fe, Zn and Mn by corn sorghum and soybeans. J. Plant Nutr. 11:1353-1360

Kaplan M, Orman S (1998) Effect of elemental sulphur and sulphur containing west in a calcareous soil in Turkey. J. Plant. Nutr. 21:1655-1665

Kacar B, Katkat AV (2007) Plant Nutrition. 3th Edn. Nobel Press; Ankara, Turkey.

Kaya M, Zeliha K, Erdal I (2009) Effects of elemental sulfur and sulfur-containing waste
on nutrient concentrations and growth of bean and corn plants grown on a calcareous soil Africa J. Biot. 8(18):4481-4489

Kayser A, Schroder TJ, Grunwald A, Schulin R (2001) Solubilization and plant uptake of zinc and cadmium from soils treated with elemental sulfur. Int. J. Phytorem. 3:381-400

Khaled AElT, Abdou AS, Maher ES, Satoshi M (2006) Isolation and characterisation of sulfur-oxidising bacteria, including strains of *Rhizobium*, from calcareous sandy soils and their effects on nutrient uptake and growth of maize (*Zea mays* L.). Aust. J. Agril. Res. 57(1):101-111

Kuo S (1996) Phosphorus. In: Methods of Soil Analysis, part 3. Chemical Methods. Sparks DL (ed.) Soil Sci. Soc. Am., Book Series no. 5 Madison, WI, USA

Lindemann WC, Aburtto JJ, Haffner WM, Bono AA (1991) Effect of sulfur source on sulfur oxidation. Soil Sci. Soc. Am. J. 55:85-90

Loeppert RH, Zuarez DI (1996) Carbonate and gypsum. In: Methods of Soil Analysis, Part 3 Chemical Methods. Sparks DL (ed.) Soil Sci. Soc. Am., Book Seriesno. 5, Mad. USA

Lopez-Aguirre JG, Larios JF, Gonzalez SG, Rosales AM, de Freitas JR (1999) Effect of sulfur application on chmical properties and microbial populations in a tropical alkaline soil. Pedobiol. 43:183-191

Marschner H (1995) Mineral Nutriton of Higher Plants. 2nd. ed. Academic Pres; San Diago, USA

Motior MR, Abdou AS, Fareed HAD, Sofian MA (2011) Responses of sulfur, nitrogen and irrigation water on *Zea mays* growth and nutrients uptake. Aust. J. Crop Sci. 5(3):347-357

Murphy J, Riley HP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36

Neilsen D, Hogue EJ, Hoyt PB, Drought BG (1993) Oxidation of elemental sulfur and acidification of calcareous orchard soils in southern British Columbia. Can. J. Soil Sci. 73:103-114

Orman S, Kaplan M (2000) Effects of two different sulfur sources on pH of calcareous soils. J. Akdeniz Univ. Agric. Faculty, 13:171-179

Rupela OP, Tauro P (1973) Utilization of *Thiobacillus* to reclaim alkali soils. Soil Biol. Biochem. 5:899-901

Saleh ME (2001) Some Agricultural Application for Biologically Produced Sulfur Recovered from Sour Gases. I- Effect on Soil Nutrients Availability in Highly Calcareous Soils. International Symposium on Elemental Sulfur for Agronomic Application and Desert Greening. UAE University, Abu Dhabi, UAE, 24-25 February, 2001

SAS (2003) Statistical Analysis Systems. SAS/STAT user's guide. Version 8.1, Cary, NC. Statistical Analysis System Institute

Shadfan H, Husssen AA (1985) Effect of sulphur application on the availability of P, Fe, Mn, Zn and Cu in selected Saudi soils. In: Proc. Sec. Reg. Conf. on Sulphur and Its
Usage in Arab Countries. Riyadh 2-5 March, 1985, Saudi Arabia. 1:3-24

Slaton NA, Norman RJ, Gilmour JT (1999) Oxidation rates of commercial elemental sulfur products applied to an alkaline silt loam from Arkansas. Soil Sci. Soc. Am. J. 65(1):239 -243

Slaton MR, Hunt ER, Smith WK (2001) Estimating near-infrared leaf reflectance from leaf structural characteristics. Am. J. Bot. 88(2):278–284

Yang ZH, Oven KS, Haneklaus S, Singh BR, Schnug E (2010) Elemental sulfur oxidation by *Thiobacillus spp*. and aerobic heterotrophic sulfur-oxidizing bacteria. Pedosphere 20(1):71-79