



# International Journal of **Soil Science**

ISSN 1816-4978



Academic  
Journals Inc.

[www.academicjournals.com](http://www.academicjournals.com)

## **Incorporation and Transformations of Elemental Sulphur in High pH Soils of Malaysia**

<sup>1,2</sup>Mehdi Karimizarchi, <sup>1</sup>Aminuddin Husin, <sup>1</sup>Mohd Khanif Yusop and <sup>1</sup>Radziah Othman

<sup>1</sup>Department of Land Management, Faculty of Agriculture, University Putra Malaysia, Serdang, Selangor, Malaysia

<sup>2</sup>Faculty of National Salinity Research Centre, Yazd, Iran

*Corresponding Author: Mehdi Karimizarchi, Department of Land Management, Faculty of Agriculture, University Putra Malaysia, Serdang, Selangor, Malaysia Tel: 0060147153212*

### **ABSTRACT**

Knowledge of elemental Sulphur (S) oxidation and its effect on soil chemical properties is seamlessly required before it can be recommended for use as a soil amendment or acidulate source. Therefore, a batch experiment was carried out to quantify various S fractions and to study how elemental S amendment affects S dynamics in Bintang series soil. Results showed that elemental S, applied up to 1 g S kg<sup>-1</sup> soil, was successfully oxidized and converted to both organic and inorganic forms. While inorganic water soluble S appeared to be the predominant form of S, comprising more than 65% of total S, for Bintang series soil amended with elemental S rate of 0.25 g S kg<sup>-1</sup> and more, organic form of S was the major form, comprising more than 96% of total S, in the soil amended with 0.125 g S kg<sup>-1</sup> and less. Regarding soil remediation, elemental sulphur will be efficient for enhancing soil micronutrient availability and it can act as a source of some micronutrients for agricultural practices in Bintang Series soil.

**Key words:** Sulphur oxidation, micronutrients release, pH

### **INTRODUCTION**

Sulphur, as an essential plant macro nutrient (Govahi and Saffari, 2006; Khan *et al.*, 2003), is a highly reactive element present in many forms that play important biological and chemical functions in the environment. While the sulphur has been used as a fungicide (Chapman, 1989), the potential medicinal uses of plants with high sulphur content has been reviewed by Sohail *et al.* (2011). Sulphate is the most abundant form of inorganic S found in most soils, as well as the main form available to plants. However, the bulk of soil S in natural and managed ecosystems is in organic form, which is directly impacted by microbial activity through decomposition processes. Sulphur dynamics is variable among soils and often closely associated with other nutrient cycles. In aerobic agricultural soils, many microbial-mediated processes are responsible for S transformations, including mineralization, immobilization and oxidation (Ye *et al.*, 2010).

The S content of Bintang series soil is seamlessly very low (<40 mg kg<sup>-1</sup> soil) and it would be decreased over time due to cultivation throughout leaching or plant uptake. The cultivation induced decrease in soil S content has been well documented (Balik *et al.*, 2009; Solomon *et al.*, 2001). Therefore, addition of soil amendments to improve soil S sources seems to be essential for successful agriculture in this area. Additionally, as Bintang series soil which is formed by limestone parent materials is high in pH and low in soil micronutrients the expectation is that decreasing the pH of Bintang series soil would improve soil nutrient availability and finally plant performance

(Cui *et al.*, 2004; Lindsay, 1979; Safaa *et al.*, 2013). Therefore, elemental S as a source of S with the acidifying and slow release character (Raja *et al.*, 2007), that is easily available, can most probably act as a source of S and concurrently as a soil amendment for agricultural practices in Bintang series soil. As minimal research data is available on elemental S transformations, this study carried out to quantify the ability of Bintang series soil in elemental S disintegration. Additionally, the effect of elemental S on the release of soil nutrient was elucidated. Considering the soil subsidence in Malaysia, the necessity of doing an explicit quantification of S transformations and budgets within Bintang series soils is magnified.

## **MATERIALS AND METHODS**

**Site description and soil sampling:** A high pH soil sample was provided (0-20 cm) from Perlis, which is affected by limestone parent materials, air dried and ground (<2 mm) before use. The soil has silt loam texture with 24.63 and 66.41% clay and silt, respectively. The sample for this study was taken from Bukit Bintang, Perlis which is under natural vegetation (forest) with 1.77 and 0.04% organic carbon and total S, respectively indicating very low amount of total S, it falls far below the value of S content in grassland soils ranging from 0.15-1.2 g S kg<sup>-1</sup> of soil (Scherer, 2009).

Six application rates of powdered elemental sulphur including 0, 0.062, 0.125, 0.25, 0.5 and 1 g kg<sup>-1</sup> of soil with three replications were used to determine S oxidation and transformations. It should be noted that laboratory grade elemental sulphur with 99.5-100.5% assay was used. Each experimental unit consists of 2 kg of soil in a plastic pot with 26 cm diameter and 10 cm height. The plastic container was sealed by plastic sheets with small holes to minimise water loss whilst maintaining aeration. The soil moisture content of all 21 experimental units were adjusted at 60% field capacity and were incubated at 25°C for up to 75 days. These were sampled at 4, 8, 13, 20, 32, 47, 53 and 75 days after incubations. Each soil sample were air-dried, grinded and analysed for different forms of sulphur such as remaining elemental S (Pansu and Gautheyrou, 2006), total water soluble S (Ye *et al.*, 2010), inorganic water soluble sulphur, sulphate as well as soil chemical properties including pH, electrical conductivity and soil nutrient concentration.

**Soil analysis:** Elemental S (ES) was measured according to Pansu and Gautheyrou (2006); 5 g of soil was shaken for 24 h with 15 cc of acetone in a centrifuge tube using an end-to-end shaker. Then a suitable aliquot of the clear supernatant liquid, 5 mL, was run into about 30 mL of distilled water in a 50 mL calibrated flask. Colloidal S begins to form immediately after the solvent has been exchanged. The liquid in the flask was then diluted to the mark with distilled water, mixed and set aside for 3 h, after which the optical density of the solution is measured. The S content of the original sample is calculated by reference to a calibration graph plotted from the results obtained when a standard solution of S in acetone is used. For Total Water Soluble Sulphur (TWSS) extraction (Ye *et al.*, 2010), 5 g of soil was shaken for 30 min with 25 mL of distilled water after addition of 5 drops of toluene. Toluene inhibits microbial activity that may oxidize or mineralize sulphur during and after extraction (Page *et al.*, 1982). To separate soil particles from the solution, the samples were centrifuged for 15 min at 3000 rpm and filtered with Whatman No. 42 filter paper. For sulphur determination ICP-OES (Perkin Elmer, Optima 8300) was used. This form of sulphurs represents both organic and inorganic form of sulphur. With each run, three blanks were carried through the entire procedure. The S content of the original sample is calculated by reference to a calibration graph plotted from the results obtained when a standard solution of S is used. For extraction of Inorganic Water Soluble Sulphur (IWSS) as bioavailable form of S (Kulhanek *et al.*,

2011) 5 g of soil was shaken with 25 mL of water for 0.5 h, after adding 5 drops of toluene. Then it was filtered through Whatman No. 42 filter and the sulphate concentration was measured by precipitation of sulphate by BaCl<sub>2</sub> and measuring the remaining Ba in solution according to Varley and Chin (1970). For better precipitation of sulphate, solutions were acidified and heated before BaCl<sub>2</sub> being added slowly. Organic Water Soluble Sulphur (OWSS) was calculated by subtracting inorganic water soluble sulphur from total water soluble sulphur (Ye *et al.*, 2010). The mobile fraction of soil nutrients was extracted by the neutral and un-buffered solution, CaCl<sub>2</sub> (Hlavay *et al.*, 2004; Jones, 2001; Ye *et al.*, 2011) as follow; 10 g air dried soil was shaken for 2 h with 100 mL of 0.01 M CaCl<sub>2</sub> solution. To obtain clear solution, it was centrifuged for 15 min at 3000 rpm and then filtered. The extracted nutrients were determined by ICP-OES (Perkin Elmer, Optima 8300). Soil pH was measured in a soil water suspension (10 g soil to 25 mL deionized water) 24 h after shaking for 30 min on a reciprocal shaker.

**Statistical analysis:** The experiment was laid out in a randomized complete block design with six rates of elemental sulphur and three replications. The SAS commands were used for analysis of variance and significant differences among individual treatments were determined with Duncan's test at  $\alpha = 0.05$ . To model the relationship between oxidized elemental sulphur and time the data were subjected to different regression models at probability level of 0.05 with the help of Sigmaplot software.

## RESULTS AND DISCUSSION

**Oxidation of sulphur:** Elemental S, applied at different rates, was disappeared in Bintang Series soil. Indicating the successful oxidation of elemental S, Table 1 shows the equation for disappearance of 6 S elemental sulphur application rates as a function of time in Bintang soil series. Elemental sulphur disappearance followed the exponential rise to maximum with R<sup>2</sup> ranging from 0.86-0.97. This exponential rise model shows that S oxidation followed a first order reaction, a reaction that proceeds at a linear rate that depends on one reactant concentration. Our finding is similar to the results obtained by Slaton *et al.* (2001) and Zhao *et al.* (1996). Using sulphur rates of 500 and 1000 kg ha<sup>-1</sup>, they found that the relationship between percentages of S oxidized and time includes two rapid and slow phases. They also emphasised that the rapid phase may present more than a single phase and more intensive sampling following S addition is needed to describe the rapid phase accurately. Among several different possible explanations as reasons for decrease in oxidation rate with time, sulphur particle size, soil properties and temperature are most important (Chapman, 1989; Slaton *et al.*, 2001; Zhao *et al.*, 1996). In contrast to the initial rapid oxidation phase found in our study and studies conducted by Slaton *et al.* (2001) and Chapman (1989) observed a lagphase at the beginning of oxidation studies. This lagphase was followed by a rapid period and plateaued near 100% oxidation. These three phases produce a sigmoidal shaped curve. The length of lag phase depends on the incubation temperature and was attributed to a time

Table 1: Elemental S disappearance equations and coefficients for bintang series soil with time for 99% disappearance

Elemental S rate (g kg <sup>-1</sup> soil)	Equation (Oxidized elemental S and time %)	R <sup>2</sup>	Days required for 99% oxidation
1.00	S = 105 [1-e <sup>(-0.041t)</sup> ]	0.98**	69.24
0.50	S = 100.30 [1-e <sup>(-0.067t)</sup> ]	0.97**	65.48
0.25	S = 98.3 [1-e <sup>(-0.088t)</sup> ]	0.96**	56.36
0.12	S = 95 [1-e <sup>(-0.132t)</sup> ]	0.94**	24.01
0.06	S = 95.32 [1-e <sup>(-0.187t)</sup> ]	0.86**	17.48

requirement for microbial population increases and the time required for microbial colonization of S particles (Chapman, 1989; Slaton *et al.*, 2001). Accordingly, it is expected that 99% of elemental S applied at rates of 1, 0.5, 0.25, 0.12 and 0.06 g S kg<sup>-1</sup> soil in Bintang series soil would be converted to oxidized form after 69, 65, 56, 24 and 17 days of incubation (Table 1), respectively. The oxidative ability of soils is of importance for agricultural practices and need to be studied. Watkinson (1989) showed that 70 days are needed for oxidation of 95% of elemental S applied at a rate of 10 g kg<sup>-1</sup>. Additionally, as total S applied to Bintang soil series was disappeared it shows that microbial activity is not an inhibitory factor for sulphur oxidation over the range of sulphur applied in our experiment.

When the applied elemental S disappeared the question arises is that it would be converted to which form or forms of S. The fate of elemental S that was oxidized may include pathways such as adsorption onto soil colloids (Shan *et al.*, 1997), incorporation into organic fraction (Khalid *et al.*, 2012; Ye *et al.*, 2010) and release as water soluble sulphate (Ye *et al.*, 2010; Zhao *et al.*, 1996), the only fraction of S that is readily available for plants and can concurrently be leached (Balik *et al.*, 2009; Shan *et al.*, 1997; Ye *et al.*, 2010). Therefore these forms of S were measured to quantify the oxidation and incorporation of S over time.

**Production of S fractions:** The results showed that elemental S transformations in Bintang series soils depend on the rate of S addition. Therefore, S transformations were summarized and presented based on the S rate that was classified in two groups including high and low S rates, with net S mineralization and immobilization, respectively. Including the rates of 0.25 g S kg<sup>-1</sup> and more, more than 65% of total S was converted to the inorganic water soluble S, where net mineralization was occurred. However, net S immobilization observed at S rates of 0.125 g S kg<sup>-1</sup> and less, with more than 96% of total S in organic form.

**High sulphur application rate:** Representing the successful oxidation and disintegration of elemental S applied at a rate of 0.25 g S kg<sup>-1</sup>, there is an upward trend in the concentration of TWSS and IWSS fractions of S over time (Fig. 1). It means that complete production of sulphate at this rate in Bintang Series soil needs at least 54 days. This is close to the time predicted, 56 days, for total oxidation of elemental S (Table 1).

Interestingly, the concentrations of the total water soluble S started to increase from the first sampling at 4 days after S incubation without a lag phase as was not observed for elemental sulphur oxidation. However, the sulphate production showed a lag phase of 4 days as was

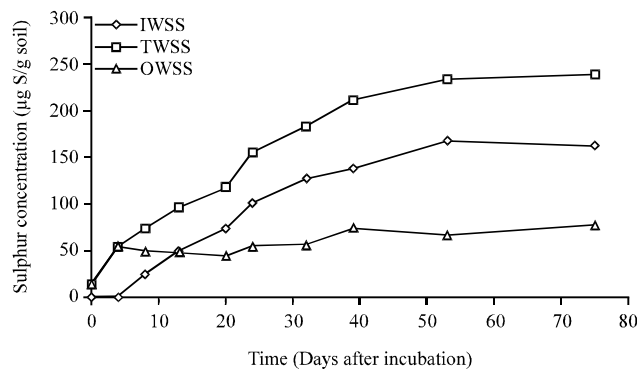


Fig. 1: Evolution of Total Water Soluble S (TWSS), Inorganic Water Soluble S (IWSS) and Organic Water Soluble S (OWSS) with time in Bintang series soil treated with 0.25 g S kg<sup>-1</sup> soil

previously reported (Chapman, 1989). This observation supports the fact that S immobilization is the predominant process at the beginning of S oxidation process that followed by the S mineralization and sulphate production, as inorganic water soluble form of S. It should be noted that the lag phase between S disappearance and sulphate production can be attributed to the time is needed for conversion of elemental sulphur taken up and transformed into intracellular sulphur globules by microorganisms to sulphate as it is stated by Franz *et al.* (2007). The initial concentration of TWSS, before application of elemental S, was  $13.5 \mu\text{g S g}^{-1}$  of soil and the sulphate was not detected. After just only 4 days of soil incubation, the total water soluble S increased 17.28 times, from  $13.5\text{-}53.63 \mu\text{g S g}^{-1}$  of soil, while the sulphate was not detected. In the other words the amount of TWSS and OWSS is the same. This reflects the fact that all of disappeared elemental S within first four days of incubation has been converted to organic form and S immobilization is the just only pathway of added S. It also shows the rapid oxidation of elemental sulphur because around 21% of total S measured was converted to water soluble sulphur within just only 4 days.

While there is still an upward trend in TWSS and IWSS, the pace of their increase was reduced after about 53 days. In terms of TWSS, the S concentration increased just only 2.1% within 22 days. This is more supported by the remaining elemental S measurements, with 99% reduction in elemental S within 56 days.

Being  $24.51 \mu\text{g S g}^{-1}$  of soil, just less than 9.8% of the added S was incorporated into Inorganic Water Soluble Sulphur (IWSS) within the first 8 days of incubation. However, 85% of measured IWSS was produced over the next 45 days.

The concentration of organic water soluble S experience a 3.97 times increase within just only first four days of soil incubation and then did not changed substantially over time. It means that the main process in S transformation is immobilization at first four days of soil incubation. However after this stage, the S mineralization is the predominant process. This observation is also supported by the upward trend in inorganic water soluble sulphur,  $\text{SO}_4^{-2}$ , over the time.

After 75 days of soil incubation, organic water soluble S represented on the average 22.71% of the total S, while inorganic water soluble sulphur accounted for 65.95%, being the dominant S fraction at the end of experiment. It is well documented that when elemental sulphur is applied in the soil it would be taken up by micro-organisms and transformed into intracellular sulphur globes and finally oxidises to sulphate (Franz *et al.*, 2007). At this stage, the total water soluble and total organic form of sulphur comprises 87.9 and 34.8% of the S pool with just only 12.1% being in organic form that was not extracted by water. This shows the importance of water soluble form of sulphur as it can be uptake by plants or lost through leaching. The importance of S leaching and cultivation on soil S content decrease was stated by Schmidt *et al.* (2012), Solomon *et al.* (2001) and Balik *et al.* (2009). As the oxidation of elemental sulphur is fast in Bintang series soil and it can be lost through leaching, the split application of elemental sulphur for providing plant needs can be recommended.

**Low sulphur application rate:** While TWSS production trend in soils treated  $0.125 \text{ g S kg}^{-1}$  (Fig. 2) was similar to the S addition rate of  $0.25 \text{ g S kg}^{-1}$ , the concentration of sulphate, IWSS, did not substantially changed over time. Likewise the S rate of  $0.25 \text{ g kg}^{-1}$  of soil, TWSS started to increase from the first sampling at 4 days after S incubation and immobilization was the just only pathway of S transformation. After 8 days, IWSS amounted  $1.20 \mu\text{g S g}^{-1}$  of soil and its low concentration, being far less than TWSS, that continued to the end of the experiment refers to S immobilization as the predominant pathway of S added at a rate of  $0.12 \text{ g S kg}^{-1}$  of Bintang series soil.

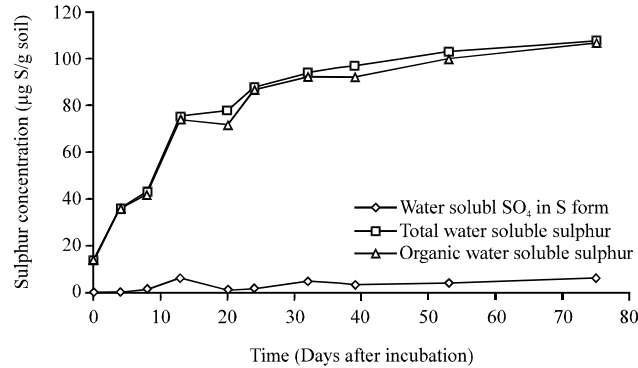


Fig. 2: Changes and distribution of S between Total Water Soluble S (TWSS), Inorganic Water Soluble S (IWSS) and Organic Water Soluble S (OWSS) with time in Bintangseries soil treated with 0.125 g S kg<sup>-1</sup> soil

Table 2: Effect of elemental sulphur on soil nutrient release

S rate	Soil pH	Soil nutrient concentration (mg kg <sup>-1</sup> soil)	
		Fe	Mn
0.00	7.25	0.05b†	2.340 <sup>b</sup>
0.06	7.07	0.155 <sup>b</sup>	2.560 <sup>b</sup>
0.25	6.77	0.055 <sup>b</sup>	3.300 <sup>b</sup>
1.00	4.86	0.755 <sup>a</sup>	31.089 <sup>a</sup>

†Means within column followed by the same letter are not significant at the 0.05 level, according to Tukey test. Values denoted the means across incubation time, ‡Tr-traces

Regarding total S measured, the C/S ratio in soil would be 105 that is less than 200, the value that is needed for S mineralization (Eriksen, 2009). As it was expected, at this C/S ratio, the S mineralization took place but concurrently S immobilization as the predominant pathway was occurred. This rapid S immobilization can be accounted for the burst of biological activity as outlined by McLaren *et al.* (1985).

The immobilization of S as the main process in S transformation at the rate of 0.12 g S kg<sup>-1</sup> Bintang series also can be supported by assessing the concentration of organic water soluble S (Fig. 2). The OWSS, being far more than IWSS, experienced a 264% increase within just only first four days of soil incubation and this upward trend continued over time. It means that the main process in S transformation is immobilization until the end of the experiment. Like other higher S application rates, it reflects that elemental S first converts to organic form and then after a lag phase of 8 days, the inorganic form of S is produced.

At the final sampling period (75 days of incubation), TWSS concentrations was 107.71 µg S g<sup>-1</sup> of soil. While this implies that 64.88% of soil S is water soluble, it also refers that 58.29 µg S g<sup>-1</sup> of soil, 35.11%, has not extracted by water. As exchangeable form of S, measured 9 times during the period of experiment, was not detected, this can be accounted for the un-extracted organic forms of S.

**Soil nutrient release in batch experiment:** It is believed that soil nutrient concentration and uptake by plants highly affects by soil acidification (Lindsay, 1979; Marschner, 2012; Wang *et al.*, 2006). As application of elemental S substantially decreased Bintang Series soil pH (Table 2),

the solubility of soil nutrients in un-amended soil and the soils treated with 1, 0.25 and 0.06 g S kg<sup>-1</sup> soil were measured to quantify the effect of sulphur application rate on soil nutrient release. The change in soil nutrient availability needs a specific decrease in soil pH and therefore specific sulphur application rate and varied with nutrient element. For instance while the Cu concentration was not found in detectable amount over the range of sulphur applied, the Fe and Mn significantly increased at highest S rate of 1 g S kg<sup>-1</sup>.

Ranging from 0.05 to 0.125 mg kg<sup>-1</sup> soil, application of elemental sulphur up to 0.25 g S kg<sup>-1</sup> soil had not significant effect on Fe concentration at 5% probability level (Table 2), however addition of 1 g S kg<sup>-1</sup> soil significantly increased Fe concentration in soil, 1500% from 0.05 to 0.755 mg kg<sup>-1</sup> soil. The increase in soil iron release is due to soil pH reduction from background of 7.25 to 4.86 as a result of elemental sulphur oxidation. Accordingly, soil pH for sulphur application rates of 0, 0.06, 0.25 and 1 g S kg<sup>-1</sup> soil at the end of experiment were 7.25, 7.07, 6.77 and 4.86, respectively. In the other words, soil pH reduction up to 6.77 was ineffective in soil Fe release. As stated by Lambers *et al.* (2008) and Viani *et al.* (2014), the increasing of weathering rate, the change in oxidation state of some nutrients and the displace of cations from exchangeable sites due to high concentration of hydrogen ions account for the increases in soil nutrient mobility. The solubility of Mn due to application of elemental sulphur up to 0.06 g S kg<sup>-1</sup> soil was not affected. Indicating the specific pH is needed for increase in soil nutrient release, the ineffectiveness of soil pH reduction, from 8 to 7 through elemental sulphur application, on Fe, Zn, Ni and Cu was observed by De la Fuente *et al.* (2008). However, addition of 1 g S kg<sup>-1</sup> soil significantly increased soil Mn concentration, 13.51 times from 2.3-31.09 mg kg<sup>-1</sup> soil (Table 2). This is in line with positive effect of soil pH reduction due to S application on soil nutrient release and plant performance that was reported by Shenker and Chen (2005). Interestingly, the Zn and Al concentration was not found in detectable amount up to addition of 0.25 g S kg<sup>-1</sup> soil (Table 2). However, they amounted to 0.14 and 0.11 mg kg<sup>-1</sup> at highest S rate. The increase in Al mobility at highest S rate may negatively affect the plant performance and needs to be studied more (Bennet *et al.*, 1986; Tan *et al.*, 1993).

## CONCLUSION

As Bintang Series soil with alkaline pH of 7.3 is low in available and total sulphur, it is essential to enhance S pools for successful agricultural practices. Elemental sulphur as a source of sulphur was successfully oxidized, following non-linear regression model of exponential rise to the maximum and converted to plant available species. Water soluble species comprises 16.07, 55.89, 64.88, 87.9, 85.23 and 95.8% of total S in soils treated with 0, 0.06, 0.12, 0.25, 0.5 and 1.00 g S kg<sup>-1</sup>, respectively.

The criteria used to trace elemental sulphur transformations showed a two stages of fast disappearance or production followed by a slow phase, however the lag phase was found just only for sulphate, IWSS, production.

Both elemental sulphur disappearance, quantified by spectrophotometer and sulphate production can be used as a criteria to predict the elemental sulphur oxidation and transformations. However, the first option, being cost effective and more user friendly, is preferred in the dearth of advanced instruments such as ICP or HPLC, especially in developing countries.

On average, 65 µg S g<sup>-1</sup> soil is not easily available for plants. This refers to the fact that the Bintang Series soil can retain around 65 µg S g<sup>-1</sup> of soil. Regarding the bulk density of 1.3 and root zone of 20 cm, it would be equal to 160 tons per hectare of elemental S.



Regarding remediation role of elemental sulphur on soil chemical properties, it was efficient for enhancing soil micronutrient release and can act as a source of Fe, Mn and Zn for agricultural practices in Bintang Series soil, without extra costs of production. As available Cu was not found in detectable amount and its total content amounted very low, 0.08 mg kg<sup>-1</sup> of soil, it seems that enrichment of copper pools is essential for sustainable agriculture in this area.

## REFERENCES

- Balik, J., M. Kulhanek, J. Cerny, J. Szakova, D. Pavlikova and P. Cermak, 2009. Differences in soil sulfur fractions due to limitation of atmospheric deposition. *Plant Soil Environ.*, 55: 344-352.
- Bennet, R.J., C.M. Breen and M.V. Fey, 1986. Aluminium toxicity and induced nutrient disorders involving the uptake and transport of P, K, Ca and Mg in *Zea mays* L. *South Afr. J. Plant Soil*, 3: 11-17.
- Chapman, S.J., 1989. Oxidation of micronized elemental sulphur in soil. *Plant Soil*, 116: 69-76.
- Cui, Y., Y. Dong, H. Li and Q. Wang, 2004. Effect of elemental sulphur on solubility of soil heavy metals and their uptake by maize. *Environ. Int.*, 30: 323-328.
- De La Fuente, C., R. Clemente and M.P. Bernal, 2008. Changes in metal speciation and pH in olive processing waste and sulphur-treated contaminated soil. *Ecotoxicol. Environ. Saf.*, 70: 207-215.
- Eriksen, J., 2009. Soil sulfur cycling in temperate agricultural systems. *Adv. Agron.*, 102: 55-89.
- Franz, B., H. Lichtenberg, J. Hormes, H. Modrow, C. Dahl and A. Prange, 2007. Utilization of solid elemental sulfur by the phototrophic purple sulfur bacterium *Allochromatium vinosum*: A sulfur K-edge X-ray absorption spectroscopy study. *Microbiology*, 153: 1268-1274.
- Govahi, M. and M. Saffari, 2006. Effect of potassium and sulphur fertilizers on yield, yield components and seed quality of spring canola (*Brassica napus* L.) seed. *J. Agron.*, 5: 577-582.
- Hlavay, J., T. Prohaska, M. Weisz, W.W. Wenzel and G.J. Stinger, 2004. Determination of trace elements bound to soil and sediment fractions (IUPAC Technical Report). *Pure Applied Chem.*, 76: 415-442.
- Jones, Jr. J.B., 2001. *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. CRC Press, Washington, DC., USA., ISBN-13: 9781420025293, Pages: 384.
- Khalid, R., K.S. Khan, M. Islam, M. Yousaf and G. Shabbir, 2012. Effect of different sulfur levels from various sources on *Brassica napus* growth and soil sulfur fractions. *J. Chem. Soc. Pak.*, 34: 1023-1031.
- Khan, A.R., D.I. Khan, I. Haq, I. Hussain, M. Sajid and S.A. Siddiqui, 2003. Control of common scab of potato through seed treatment. *Plant Pathol. J.*, 2: 141-144.
- Kulhanek, M., J. Cerny, J. Balik, V. Vanek and O. Sedlar, 2011. Influence of the nitrogen-sulfur fertilizing on the content of different sulfur fractions in soil. *Plant Soil Environ.*, 57: 553-558.
- Lambers, H., F.S. Chapin III and J.L. Pons, 2008. *Plant Physiological Ecology*. 2nd Edn., Springer-Verlag, New York.
- Lindsay, E.L., 1979. *Chemical Equilibria in Soils*. 1st Edn., John Wiley and Sons, New York.
- Marschner, P., 2012. *Marschner's Mineral Nutrition of Higher Plants*. 3rd Edn., Academic Press, San Diego, ISBN: 9780123849052, Pages: 651.
- McLaren, R.G., J.I. Keer and R.S. Swift, 1985. Sulphur transformations in soils using sulphur-35 labelling. *Soil Biol. Biochem.*, 17: 73-79.
- Page, A.L., R.H. Miller and D.R. Keeny, 1982. *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties, Volume 2*. 2nd Edn., America Society of Agronomy, Madison, WI., USA., ISBN-13: 9780891180722, Pages: 1159.

- Pansu, M. and J. Gautheyrou, 2006. Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods. Springer, The Netherlands, ISBN-13: 9783540312109, Pages: 993.
- Raja, A., K. Omar Hattab, L. Gurusamy and S. Suganya, 2007. Sulphur levels on nutrient uptake and yield of sesame varieties and nutrient availability. *Int. J. Soil Sci.*, 2: 278-285.
- Safaa, M.M., S.M. Khaled and S. Hanan, 2013. Effect of elemental sulphur on solubility of soil nutrients and soil heavy metals and their uptake by maize plants. *J. Am. Sci.*, 9: 19-24.
- Scherer, H.W., 2009. Sulfur in soils. *J. Plant Nutr. Soil Sci.*, 172: 326-335.
- Schmidt, F., F.D. de Bona, C.P. Silveira and F.A. Monteiro, 2012. Soil sulfur fractions dynamics and distribution in a tropical grass pasture amended with nitrogen and sulfur fertilizers. *J. Plant Nutr. Soil Sci.*, 175: 60-67.
- Shan, X.Q., B. Chen, T.H. Zhang, F.L. Li, B. Wen and J. Qian, 1997. Relationship between sulfur speciation in soils and plant availability. *Sci. Total Environ.*, 199: 237-246.
- Shenker, M. and Y. Chen, 2005. Increasing iron availability to crops: Fertilizers, organo-fertilizers and biological approaches. *Soil Sci. Plant Nutr.*, 51: 1-17.
- Slaton, N.A., R.J. Norman and J.T. Gilmour, 2001. Oxidation rates of commercial elemental sulfur products applied to an alkaline silt loam from arkansas. *Soil Sci. Soc. Am. J.*, 65: 239-243.
- Sohail, M.N., A. Karim, M. Sarwar and A.M. Alhasin, 2011. Onion (*Allium cepa* L.): An alternate medicine for Pakistani population. *Int. J. Pharmacol.*, 7: 736-744.
- Solomon, D., J. Lehmann, M. Tekalign, F. Fritzsche and W. Zech, 2001. Sulfur fractions in particle-size separates of the sub-humid Ethiopian highlands as influenced by land use changes. *Geoderma*, 102: 41-49.
- Tan, K., W.G. Keltjens and G.R. Findenegg, 1993. Aluminum toxicity in sorghum genotypes as influenced by solution acidity. *Soil Sci. Plant Nutr.*, 39: 291-298.
- Varley, J.A. and P.Y. Chin, 1970. Determination of water-soluble sulphate in acidic sulphate soils by atomic-absorption spectroscopy. *Analyst*, 95: 592-595.
- Viani, R.A., R.R. Rodrigues, T.E. Dawson, H. Lambers and R.S. Oliveira, 2014. Soil pH accounts for differences in species distribution and leaf nutrient concentrations of Brazilian woodland savannah and Seasonally Dry forest species. *Perspect. Plant Ecol. Evol. Syst.*, 16: 64-74.
- Wang, A.S., J.S. Angle, R.L. Chaney, T.A. Delorme and R.D. Reeves, 2006. Soil pH effects on uptake of Cd and Zn by *Thlaspi caerulescens*. *Plant Soil*, 281: 325-337.
- Watkinson, J.H., 1989. Measurement of the oxidation rate of elemental sulfur in soil. *Soil Res.*, 27: 365-375.
- Ye, R., A.L. Wright, W.H. Orem and J.M. McCray, 2010. Sulfur distribution and transformations in everglades agricultural area soil as influenced by sulfur amendment. *Soil Sci.*, 175: 263-269.
- Ye, R., A.L. Wright and J.M. McCray, 2011. Seasonal changes in nutrient availability for sulfur-amended everglades soils under sugarcane. *J. Plant Nutr.*, 34: 2095-2113.
- Zhao, F.J., S.Y. Loke, A.R. Crosland and S.P. McGrath, 1996. Method to determine elemental sulphur in soils applied to measure sulphur oxidation. *Soil Biol. Biochem.*, 28: 1083-1087.