Songklanakarin J. Sci. Technol.
32 (6), 643-652, Nov. - Dec. 2010

Songklanakarin Journal of Science and Technology
http://www.sjst.psu.ac.th

Original Article

The effectiveness of sulfidic materials as a source of sulfur fertilizer for the production of rice in two sulfur deficient soils

Abul Hasnat M. Shamim[1,2]*, Md. Harunor Rashid Khan[3] and Takeo Akae[1]

[1] *Department of Environmental Management Engineering, Faculty of Environmental Science and Technology, Okayama University, Okayama, Japan.*

[2] *School of Agriculture and Rural Development, Bangladesh Open University, Gazipur, Bangladesh.*

[3] *Department of Soil, Water and Environment, University of Dhaka, Dhaka, Bangladesh.*

Received 4 August 2010; Accepted 30 December 2010

Abstract

The effectiveness of sulfidic materials (SM) and gypsum (G) application at the rates of 0, 40, 80, 120, and 160 kg S ha^{-1} on the growth, yield, and mineral nutrition of rice *(Oryza sativa* L.; BR 16: Shahi balam) cultivated in two sulfur deficient soils of Sirajgonj (Typic Haplaquept) and Gazipur (Typic Paleustult) were evaluated in a greenhouse study. The best growth, yield performance, and nutrition of rice were recorded by the SM_{160} treatment in both the Sirajgonj (e.g. grain: 9.8 g/plant) and Gazipur (8.6) soils, followed by the SM_{120} (8.5, 7.5) > SM_{80} (7.3, 7.3) > G_{160} (7.1, 6.9) treatments. The application of SM increased the average grain yield by 82% (increased over control: IOC) for Sirajgonj soil and 78% for Gazipur soil, irrespective of application rates. In the case of gypsum, these increments were 40 and 37% for Sirajgonj and Gazipur soils, respectively. The application of gypsum at the highest rate of G_{160} was not as effective as even the dose of SM_{80} in both of the soils. However, almost similar and significant ($p \leq 0.05$) effects were observed for the grain weight, percent filled grains, and harvest index of rice grown in both the soils. The applied SM increased the average organic matter and available sulfur contents in the soils by 20 to 46%, and 140 to 228% IOC, respectively, while these increments were 6 to 20% and 88 to 187% for gypsum treatments, indicating that the SM was potential and effective than gypsum not only as a source of sulfur fertilizer but also to enrich the fertility and productivity status of the soils. Moreover, the SM treatment was found to be maintained the high nutrient status in both the soils till the final harvest at maturity of rice, reflecting a good indication for its long term use. The use of SM did not show any adverse effect on the plant and soil.

Keywords: effectiveness of sulfidic materials, gypsum, sulfur deficient soils, growth-yield and nutrition of rice

1. Introduction

Over the last two decades, sulfur (S) deficiency has been recognized as a constraint on crop production all over the world (Eriksen *et al.*, 2004; Girma *et al.*, 2005; Schonhof *et al.*, 2007; Mascagni *et al.*, 2008) becoming a limiting factor to higher yields and fertilizer efficiency. The main reasons are the reduction of sulfur dioxide emission from power plants and various industrial sources, the increasing use of high-analysis low-S-containing fertilizers, the decreasing use of S-containing fungicides and pesticides and high-yielding varieties (Scherer, 2001; Eriksen *et al.*, 2004). Until recently little attention has been given to the problem of sulfur deficiency in soils.

* Corresponding author.
Email address: abulhasnats@yahoo.com

According to estimates of The Sulphur Institute (TSI) based on crop demand, fertilizer efficiency and current inputs, the current S deficit is about 9.6 million tones annually. With increased food production raising S requirements and assuming slower expansion rates for S application, this S deficit is projected to grow to 11.9 million tones by 2015 (Ming Xian and MESSICK, 2007) In Asia: In the late 1990s and early 2000s, intensified agricultural production, pressured by the backdrop of food self-sufficiency goals and limited land resources in the globe's two most populous nations, China and India, has created the S nutrient imbalance. This imbalance is expected to grow due to the widespread gap between available production and supply, and crop requirements. Asia's annual S fertilizer deficit is projected to increase from over 5 million tones currently to 6.4 million tones by 2014, with over 70% represented by China and India (Ming Xian FAN, 2007).

Intensive cropping has been resulting higher removal of sulfur among the other nutrients rather its replenishment under natural process (Balsa *et al.*, 1996). Bangladesh is not free from this threat. About 7 M ha (about 52%) of agricultural lands are reported to consists of sulfur deficient soils in the Northern region of Bangladesh (SRDI, 1999). The current intensive use of agricultural land for crop production has extended the sulfur deficient areas to about 80% (Khan *et al.*, 2007). Poor crop production as a result of acute sulfur deficiency has frequently been reported by many scientists in different regions of India (Tiwari *et al.*, 1985) and Bangladesh (Khan, 2000). The current use of gypsum, ammonium sulfate, zinc sulfate, and others as sulfur fertilizers to the soils can instantly supply the sulfur to crops but the fertilization has to be done for each crop in every year, which was even unable to give satisfactory yield of crop and it is not a good practice for the soils as well as environments. Therefore, a suitable and sustainable source of sulfur is indispensable.

The use of sulfidic materials (SM) or layers obtaining from acid sulfate soils (ASSs) as sulfur fertilizer for crop production is very scanty. Khan *et al.* (2002) reported that the high organic matter (2-9 %), total sulfur (3-7 %) and micronutrients in the ASSs or SM deserve attention to use these soil materials for the reclamation of alkaline, calcareous or sulfur deficient soils and the ASSs themselves. Since the SM in ASSs has been exerting severe effects on surrounding ecosystems, immediate steps should be taken to consider these soils further. Moreover, the availability of land for growing crops is limited; it may become inevitable to utilize marginal and/or problem soils. The present studied SM is an ASS layer, which occupied 0.7 M ha of land area, had low pH (<3), high sulfate and organic matter (Khan *et al.*, 2006). When these layers of the soils are exposed to air and water, sulfuric acid is produced which causes many problems on the land and in the water. Orndorff and Daniels (2002) reported that exposure of SM from road construction presents a number of technical, environmental, and social problems. Technical problems are primarily related to the degradation of construction materials, weathering of sulfides exposed along road cuts or in fill material, and limitation of roadside vegetation, which promotes erosion. Delayed effects of potential chemicals stored in the SM resulted in harmful effects, like a "chemical time bomb" on the associated environments (Khan and Adachi, 1999).

The removals of SM from the ASSs not only reclaim the ASSs for long time but its use in sulfur deficient or non-fertile soils at the rate of about 300 to 1500 kg ha^{-1} may lead to productive fields for various crops. Khan *et al.* (2007) reported that the application of SM @ 75 kg S ha^{-1} for sulfur deficient soils had no negative effect on the soils and crop production. They suggested that the application of SM was not only effective as sulfur fertilizer but also acted for the enrichment of organic matter in the soils.

Considering the above facts, the present study was considered to evaluate the potentiality and effectiveness of the SM or ASSs in comparison with gypsum as sulfur fertilizer in relation to rice production in sulfur deficient soils, which is not only a new approach for the alternative use of SM but also might solve the problems of the utilization and management of the ASSs and recover sulfur deficiency as well.

2. Materials and Methods

2.1 Soil collection and analyses

A bulk samples of two sulfur deficient soils (depth: 0-20 cm) of Kamarkhond Series of Sirajgonj soil (Typic Haplaquept) and Kalma Series of Gazipur soil (Typic Paleustult) were collected, respectively, from the districts of Sirajgonj and Gazipur in Bangladesh. The sulfidic materials (SM: Cheringa acid sulfate soil) used for this study was obtained from the surface soil (depth: 0-20 cm) at Dulhazara in the Cox' Bazar district of Bangladesh. This SM contained high organic matter and sulfur but had low base saturation. Selected physical and chemical properties of the initial soils, SM and the average of soil data of all the treatments at post harvesting of rice were presented in Table 1.

After treatment with 1M CH_3COONH_4 (pH 5.0) and with 30% H_2O_2 to remove free salts and organic matter, respectively, particle size distribution was determined by the pipette method (Day 1965). Soil pH was measured in the field using Hellige-Truox test-kit and for the oven dried soil -0.02M $CaCl_2$ (1:2.5) suspension (Jackson, 1973) using a Corning pH meter Model-7. For saturation extract of soils, the electrical conductivity (Richards, 1954), water soluble Na^+ and K^+ (flame photometry: Black, 1965), Ca^{2+} and Mg^{2+} (atomic absorption spectrometry: Hesse, 1971) were determined. Organic matter content was determined (Nelson and Sommers, 1982) by wet combustion with $K_2Cr_2O_7$. Available N (1.3 M KCl extraction; Jackson, 1973), available P (0.002 N H_2SO_4, pH 3 extraction, Olsen *et al.*, 1954) and available S ($BaCl_2$ turbidity; Sakai, 1978) were determined. Cation exchange capacity was determined by saturation with 1 M CH_3COONH_4 (pH 7.0), ethanol washing, NH_4^+ displacement

Table 1. Some selected properties of the initial soils (depth: 0-20 cm, oven-dry basis), sulfidic materials and the average soil (0-20 cm) data of all the treatments at post harvesting of rice used during pot experiment.

Soil properties	Sirajgonj soil			Gazipur soil			¶SM (‡ASSs)
	Before use	After use	% †IOC	Before use	After use	% IOC	
Textural class	Silty loam	Silty clay loam (SCL)	SCL				
Soil pH (Field)	6.2	6.1	-	5.8	5.6	-	3.8
Soil pH (Soil:Water=1: 2.5)	6.1	5.9	-	5.5	5.2	-	3.6
Soil pH ($CaCl_2$=1.2.5)	5.8	5.6	-	5.2	4.9	-	3.3
E C (1: 5 dS m^{-1})	1.1	1.8	63.6	1.3	2.2	69.2	18.5
Organic matter (g kg^{-1})	12.2	16.1	32.0	7.1	9.2	29.6	39.1
Extractable N (mM kg^{-1})	0.23	0.3	30.4	0.2	0.25	25.0	3.6
Available P (mM kg^{-1})	0.1	0.12	20.0	0.12	0.14	16.7	0.10
CEC (c mol kg^{-1})	16.9	17.3	2.67	17.1	17.8	4.1	17.2
Base saturation (%)	74.4	80.2	7.8	66.5	72.1	8.4	24.3
Exchangeable cations (c mol kg^{-1})	-		-	-			
Sodium	0.41	0.75	82.9	0.37	0.65	75.7	2.13
Potassium	0.08	0.15	87.5	0.07	0.14	100.0	0.24
Calcium	6.48	6.6	2.31	6.5	6.62	2.6	0.31
Magnesium	3.98	4.5	13.6	3.6	4.0	10.5	0.95
Water soluble cations (c mol kg^{-1})	-		-	-			
Sodium	0.14	0.19	35.7	0.12	0.21	75.0	3.0
Potassium	0.28	0.4	42.9	0.24	0.32	33.3	0.30
Calcium	6.43	6.7	3.6	3.8	3.9	3.7	0.30
Magnesium	2.88	4.2	46.5	2.6	3.6	36.4	3.3
Available sulfur	0.03	0.09	200.0	0.04	0.10	150.0	24.4
Total sulfur	1.4	2.0	40.0	1.6	2.9	84.0	165.6

†IOC = Increased over control, ‡ASSs = Acid sulfate soils, ¶SM = Sulfidic materials

with acidified 10% NaCl, and subsequent analysis by steam (Kjeldhal method) distillation (Chapman, 1965). Exchangeable Na^+, K^+, Ca^{2+}, and Mg^{2+} were extracted with 1 M CH_3COONH_4 (pH 7.0) and determined by flame photometry (Na^+, K^+) and atomic absorption spectrophotometer. Total S was obtained by digestion with a mixture of concentrated HCl/HNO_3 (1:3) and determined by turbidity method (Sakai, 1978).

It is noted that the bulk samples obtained from each soil were stored for a few days under field-moist conditions (by putting the soil samples and the SM into polyethylene bags in an air-tied box) just prior to laboratory analyses, when the sub-samples were air-dried and crushed to 2 mm before analyses.

2.2 Pot experiment

A pot experiment was conducted in the greenhouse at the premises of the Department of Soil, Water and Environment, University of Dhaka during the period for August to December 2002 to evaluate the effectiveness of SM in comparison with gypsum (G) as a sulfur fertilizer in relation to growth and yield performance of rice grown in two sulfur deficient soils. Two sets of experiments were set up in a completely randomized design having three replications and four sampling times for each treatment. The doses of SM and gypsum were selected based on the sulfur requirement of the country as reported by BARC (1997). The experimental treatments for the soils are: Control (no application of G and SM); G_{40}, $G_{80,}$ $G_{120,}$ and G_{160} (G 40, 80, 120, and 160 kg S ha^{-1}); SM_{40}, $SM_{80,}$ $SM_{120,0}$and SM_{160} (SM 40, 80, 120, and 160 kg S ha^{-1}).

Ten kg of air-dried and screened (5 mm sieve) soil was placed in each earthen pot (Size: 36 cm height/28 cm diameter). The soil in each pot was fertilized with N, P, and K at the rates of 60, 30, and 20 mg kg^{-1} as urea, triple super phosphate (TSP) and murate of potash (MP), respectively. The full dose of TSP and MP and half of urea were mixed with the soil during pot preparation. The remaining urea was applied in equal splits, one at the active tillering stage of rice and the other at the panicle initiation stage. As per treatments, the soils in the pots were also subjected to the application of SM and gypsum at the rates of 0, 40, 80, 120, and 160 kg S ha^{-1} during pot preparation. Both the SM and gypsum were dried, milled and sieved by 1 mm sieve. Thirty-day-old healthy and uniform seedlings (*Oryza sativa* L., BR 16: Shahi balam) were transplanted at the rate of three plants per hill and four hills per pot. The seedlings were transplanted on 21[st] August'02 and harvested on 9[th] December 2002. The soils in the pots were irrigated by tap water (pH 6.5, EC 0.05 S m^{-1} and S 0.01 c mol kg^{-1}) whenever necessary, to maintain the soil under moist to wet conditions required for the production of rice. Seedlings were collected by the courtesy of Bangladesh Rice Research Institute (BRRI), Gazipur.

2.3 Plant collection and analysis

Plant height, number of tillers and shoot or straw dry matter yield were determined at 30 (20-35 early tillering stage = ETS), 60 (36-65 maximum tillering stage = MTS), 90 (66-90 panicle initiation stage = PIS) and 110 (harvesting at maturity) days after transplanting (DT). At maturity, straw and grain yield, percentage of filled grains and weight of thousand grains of rice were determined. After the crops were harvested at maturity, composite samples of shoot dry matter were analyzed for N content by the micro-Kjeldahl method (Jackson, 1973); P content by spectrometry (Jackson, 1973); S content by turbidometry (Jackson, 1973) method.

2.4 Statistical analysis

The level of significance of the different treatments was determined at different stages of growth using Duncan's New Multiple Range Test (DNMRT) and least significant difference (LSD) techniques (Zaman *et al.*, 1982). Some selected data are presented as means ± standard error (SE) of three replicates.

3. Results and Discussion

3.1 Sulfidic materials

The SM was collected from the surface (depth: 0-20 cm) of an acid sulfate soil (Typic Sulfic Halaquept, details: Khan *et al.*, 2006) showed a silty clay loam texture with pH values of 3.3 (0.02 M $CaCl_2$: lab) and 3.8 (Field), indicating that the SM had probably accumulated a large amount of pyrite which had produced H_2SO_4 in the laboratory by oxidation. The EC, available and total sulfur, and content of organic matter in the SM were very high while the base saturation was very low (Table 1). The SM was in fact a fertile but unproductive soil due to its high acidity, salinity and imbalance of nutrients. Khan *et al.* (1994) had reported that the content of Ca in SM was low in comparison with the Mg content, presumably be due to occasional flooding with sea water with the high Mg content.

3.2 Conditions of initial and post harvested soils

The Sirajgonj soil and Gazipur soil had silty loam and silty clay loam textures, initial pH values of 5.8 to 6.2 and 5.0 to 5.2, respectively as determined by the different conditions. These sulfur deficient soils were subjected to the application of SM and gypsum in relation to rice production. The pH values in different conditions of the average soil data of all the treatments at post harvesting were found to be decreased by 0.1 to 0.3 pH units compared with the initial Sirajgonj soil and Gazipur soil, indicating that the use of the acidic SM to these soils had very negligible influences on the pH of the soils. On the other hand, the SM strikingly increased the initial low contents of the organic matter, N, P, K and Mg, available and total sulfur in both the soils in comparison with the initial soils (Table 1). It was due to the high nutrient status of the applied SM.

The base saturation of the initial Sirajgonj soil was 74% which was increased to 80 % at the final harvesting of rice, while this increment was from 67 to 72% for Gazipur soil. These increases in base saturation were attributed to the high contents of basic cations in the applied SM. The EC values of the soils were found to be increased from 1.1 to 1.8 dS m^{-1} for Sirajgonj soil and from 1.3 to 2.2 dS m^{-1} for Gazipur soil, which are attributed to the higher EC value of the SM used. However, these increased levels of EC values might not have remarkable influence on the production of rice. Moreover, it was a pot experiment, when it will be conducted under field condition then the EC value will not increase up to that extend due to having more chances of dilution and leaching from the soils.

3.3 Sulfur and organic matter in the soils

The content of available sulfur in the soils were found to be increased by the treatments, despite of soil conditions and the increments were significantly ($p \leq 0.05$) stronger with the passes of time (Figure 1 and 2). These effects were most pronounced with the highest rate of SM_{160} fertilization followed by the second and third highest dose of SM_{120}, SM_{80} which was almost equally effective to the highest rate of G_{160} in both the soils. Apart from fertilizer rates, the applied SM and gypsum increased the average available sulfur contents by 228 and 187% IOC for Sirajgonj soil; 140 and 88% for Gazipur soil, respectively, at post harvesting of rice at maturity. It means the SM exerted better response for the increment of sulfur in both the soils.

The content of total sulfur was found to be increased by the treatments and decreased with the advent of time but the trend of effects of total sulfur were almost similar to those observed for available sulfur contents in both the soils. On the other hand, the content of organic matter in both the soils through out the experimental period was found to be enriched a little by the different rates of gypsum fertilization, whereas almost all the doses of SM significantly ($p \leq 0.05$) increased the organic matter status in both the soils and the increments were more striking with the higher doses of SM (data not shown).

3.4 Agronomic parameters of rice

Rice growth and development is greatly affected by

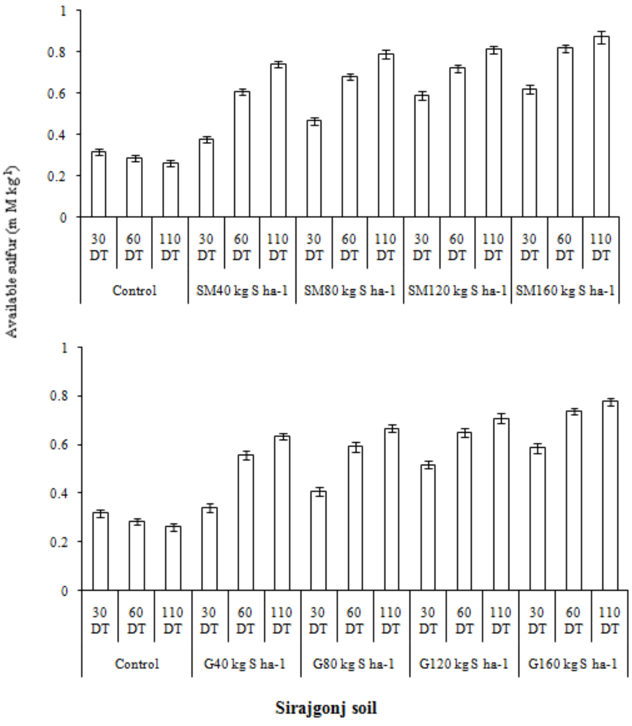

Figure 1. Effects of sulfidic materials (SM: kg S ha^{-1}) and gypsum (G: kg S ha^{-1}) on available sulfur contents at different stages of rice grown in Sirajgonj sulfur deficient soils under pot experiment (DT indicates days after transplanting). *Vertical bar* indicates ± SE of three replicates.

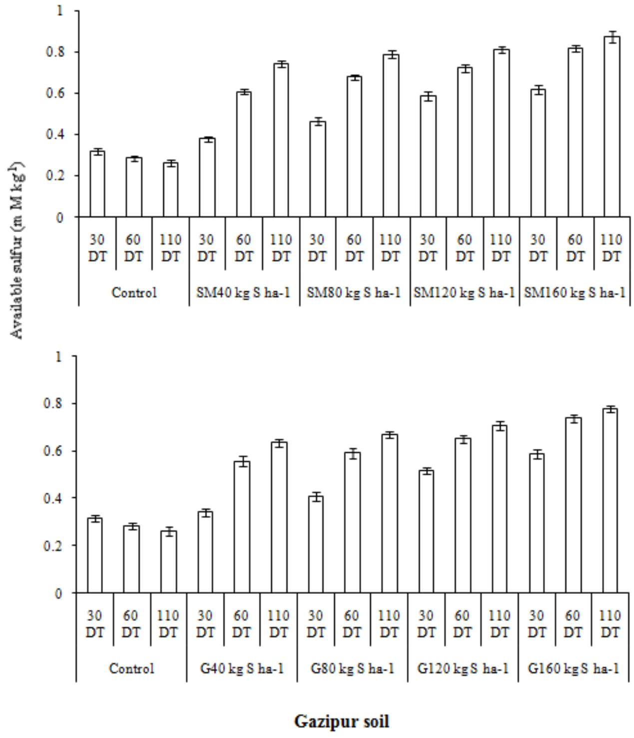

Figure 2. Effects of sulfidic materials (SM: kg S ha^{-1}) and gypsum (G: kg S ha^{-1}) on available sulfur contents at different stages of rice grown in Gazipur sulfur deficient soils under pot experiment (DT indicates days after transplanting). *Vertical bar* indicates ± SE of three replicates.

agronomic factors. The agronomic parameters like plant height, production of tiller and straw yield have important role for the understanding of visual symptoms, economic management, adaptation and use of crops. Accordingly, these parameters of rice were considered for this study. There was yellowing appeared on the younger leaves of rice in the control treatments in both the soils. The symptom of yellowing of younger leaves at the early stage of rice was also observed with the lower doses of gypsum treatments.

The application of sulfidic materials and higher rates of gypsum fertilization were found to be recovered the rice plants from that deficiency symptom. The application of sulfidic materials and gypsum exerted significant ($p \leq 0.05$) positive effects on the growth and yield of rice plants and their effects varied not only with the kinds and amounts of amending materials but also with the parameters of rice plants and soil conditions (Figure 3). The highest value of plant height and maximum number of tillers at all stages of rice growth were obtained by the application of SM_{160}, followed by $SM_{120} > SM_{80} > G_{160}$ treatments in both the soils, indicating that these amendments considerably affected by the kinds rather than the amounts of the treatments. The trends of effects of the amendments were quite similar in both the soils (Figure 3). The number of tillers at all growth stages of the rice plants increased significantly ($p \leq 0.05$) by the different rates of SM and gypsum, and the increments were most pronounced at 60 DT (MTS) followed by 90 DT (PIS) of rice (Figure 3). These results indicate that the vegetative growth of rice was much enhanced by the treatments, especially SM, which might be due to its initial high content of other nutrients rather than sulfur (Table 1).

Most of these treatments significantly ($p \leq 0.05$) varied among each other and also indicating that the application of SM at the rate of 80 kg S ha^{-1} was sometimes potential and effective than the highest rate of G_{160} treatment for the production of rice. The application of gypsum at 40 kg S ha^{-1} was found to have significant positive effects for these growth parameters but its higher rates (80, 120 kg S ha^{-1}) were somewhere not much effective. On the other hand, the application of SM strikingly increased these growth parameters and the increments were stronger with the higher rates, which were attributed not only to the high content of S in the applied SM but also the contribution of its higher fertility status. As expected, the lowest values for these plant characters were recorded in the control pots, where only basal application of N, P and K was performed. Khan *et al.* (2007) had reported that the application of SM at the rate of 75 kg S ha^{-1} increased (over control) the flower head diameter and seed yield by 77 to 80% and 169 to 182%, respectively in the sulfur deficient soils, while the same amounts sulfur fertilization from $MgSO_4$

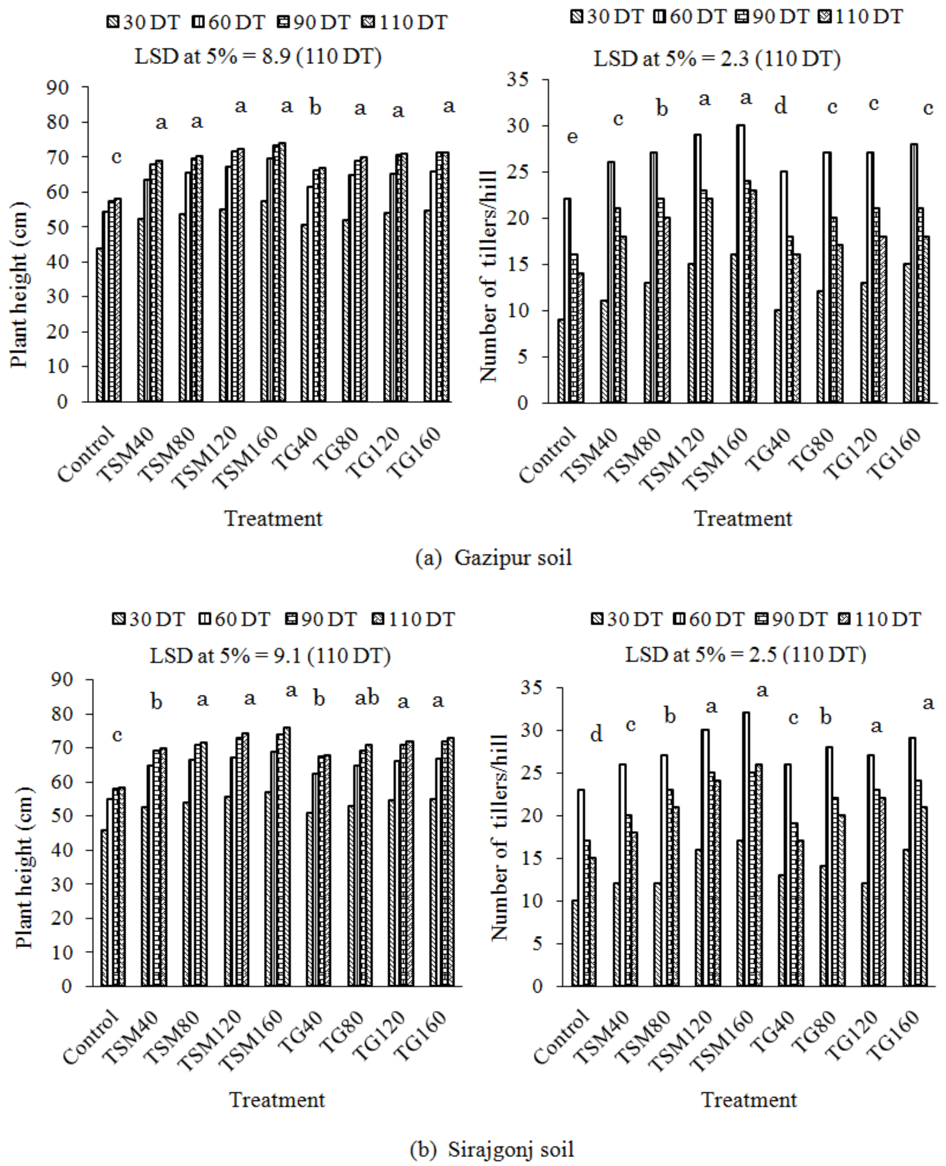

Figure 3. Effects of sulfidic materials (SM: kg S ha^{-1}) and gypsum (G: kg S ha^{-1}) on plant height and number of tillers at different stages of rice grown in two sulfur deficient soils under pot experiment (DT indicates days after transplanting).

increased those parameters by 21 to 41% and 56 to 100%.

3.5 Grain yield and yield components of rice

The maximum grain yield (9.8 g/plant for the Sirajgonj soil and 8.6 for the Gazipur soil) was recorded by the highest dose of SM_{160}, followed by the SM_{120} (8.5, 7.5), SM_{80} (7.3, 7.3), G_{160} (7.1, 6.9 g/plant) treatments in both soils (Table 2). Despite of the rates, the application of SM was found to be increased the grain yield of 82 and 78% IOC in the Sirajgonj soil and the Gazipur soil, respectively, whereas these increments were 46 and 37%, respectively, by the gypsum treatments, reflecting that the SM has a high potential against gypsum as a sulfur fertilizer.

The application of SM was exerted significant effects in increasing the grain weight and percent filled grains of rice, but the application of gypsum was found to have additive effects for these plant characters (Table 2). The grain weight, percent filled grains and the harvest index (Table 2) of the rice indicated that the SM is potential and effective compared with the conventional sulfur fertilizers, like gypsum, in terms of growth and yield performance of rice, though the effects varied with the soil conditions. Khan *et al.* (2007) had also reported that the application of SM at the rates of 25 to 75 kg S ha^{-1} was effective to increase the organic matter status in soils and enhanced the release of essential plant nutrients into the growing media, which are very essential for crop production in poor soils.

Table 2. Effects of sulfidic materials (SM: kg S ha^{-1}) and Gypsum (G: kg S ha^{-1}) as fertilizer for the growth, yield and yield components of rice grown on two sulfur deficient soils.

Treatment Denotation	Panicle length (cm)	Grain yield (g/plant)	†IOC (%) 0	Harvest index	1000 grain wt. (g)	% filled grain
Gazipur soil						
Control	17.9 c¶	4.2 e	–	0.44	17.8 c	64.2
T_{SM40}	21.2 b	6.2 c	49.9	0.46	21.8 b	71.5
T_{SM80}	21.6 b	7.3 b	75.4	0.47	22.6 b	72.8
T_{SM120}	22.5 ab	7.5 b	80.7	0.47	23.3 a	73.6
T_{SM160}	24.2 a	8.6 a	107.2	0.47	25.3 a	75.2
T_{G40}	20.3 bc	5.2 d	25.3	0.45	21.6 b	69
T_{G80}	20.9 b	5.2 d	25.5	0.46	22.3 b	71.4
T_{G120}	21.1 b	5.4 d	30.1	0.46	22.7 b	72.1
T_{G160}	21.8 b	6.9 b	66.3	0.46	23.1 a	72.3
LSD at 5 %	2.4	0.7	–	–	2.5	–
SM-IOC (%)	25	78.3		6.2	30.6	14.1
G-IOC (%)	17.5	36.8	–	4.0	26.0	10.9
Sirajgonj soil						
Control	18 c	4.3 e	–	0.43	18.5 d	65
T_{SM40}	21.5 b	5.5 d	28.5	0.45	22 c	70.9
T_{SM80}	21.7 ab	7.3 c	47.2	0.46	23.7 ab	72.8
T_{SM120}	22.8 a	8.5 b	99.1	0.47	24.5 a	73.5
T_{SM160}	23.6 a	9.8 a	129.0	0.48	25.8 a	74.2
T_{G40}	20.4 b	5.2 d	21.0	0.44	21.9 c	70
T_{G80}	21.1 b	5.3 d	22.9	0.45	23 b	71.2
T_{G120}	21.3 b	6.4 c	50.0	0.45	23.5 b	72.1
T_{G160}	21.9 ab	7.1 b	89.3	0.46	23.8 ab	72.5
LSD at 5 %	2.3	0.7	–	–	2.5	–
SM-IOC (%)	24.4	81.8		8.1	29.7	12.1
G-IOC (%)	17.6	40.0	–	4.7	24.6	9.9

¶In a columns of panicle length, grain yield and 1000 grain wt., categorized class (a, b, c, d and e) is shown. A common letter means the values do not differ significantly at 5 % level by LSD according to DNMRT (Duncan's New Multiple Range Test); †IOC (calculated from grain yield) = Increased over control.

3.6 Nutrition of rice

The highest N, P and S contents in rice shoot at different growth stages of rice were obtained by the SM_{160} followed by the 2nd highest dose of SM_{120} treatment. The SM_{80} and the highest dose of G_{160} were almost equally effective and ranked 3rd in order of nutrient contents. The lowest contents of these nutrients were recorded for the control treatments in both the soils (Table 3). The increments of these elements were significant ($p \leq 0.05$) and stronger with the higher rates of SM and the highest rate of gypsum treatments in both the soils. The average S contents in plant tissues of all the SM treatments at the final harvesting (110 DT) of rice were increased by 142% in the Sirajgonj soil and 105% in the Gazipur soil compared with the control treatments (Table 3). But these increments of S by the average of all gypsum treatments were 96 and 45% for the rice plants grown in the Sirajgonj and Gazipur soils, respectively. The striking increments in N and P were also determined by the applied SM in comparison with gypsum treatments in both the soils (Table 3). These results suggest that the SM is not only potential than gypsum fertilizer but also would be effective for the subsequent crops as indicated by the high content of nutrients in rice plants at the final harvesting (110 DT) as determined from the SM treated soils. The use of SM not only recovered S-deficiency but also improved the fertility status

Table 3. Effects of sulfidic materials (SM: kg S ha^{-1}) and Gypsum (G: kg S ha^{-1}) on the nutrients contents (g kg^{-1}) at different stages of growth of rice shoot on two sulfur deficient soils.

Treatment denotation	Nitrogen (N)		Phosphorus (P)		Sulfur (S)	
	60 DT†	110 DT	60 DT	110 DT	60 DT	110 DT
Gazipur soil						
Control	22.1	8.2 e¶	1.4	1.1 d	2.2	1.6 d
SM_{40}	23.2	9.5 c	1.8	1.5 c	2.8	2.3 c
SM_{80}	23.8	11 b	2.3	1.9 b	3.5	3.1 b
SM_{120}	24.3	12.2 a	2.6	2.2 a	4.1	3.7 a
SM_{160}	25.5	12.6 a	2.7	2.3 a	4.6	4 a
G_{40}	22.5	9.1 d	1.5	1.1 d	2.4	2 d
G_{80}	22.8	9.7 c	1.8	1.6 c	2.5	2.3 c
G_{120}	23.4	10.5 bc	2.0	1.7 b	2.9	2.4 c
G_{160}	24.1	11.4 b	2.2	1.8 b	3.4	2.8 b
LSD (5%)	–	1.2	–	0.22	–	0.38
SM-IOC (%)	9.5	38.11	67.86	79.55	70.45	104.69
G-IOC (%)	4.98	24.09	33.93	40.91	27.27	45.31
Sirajgonj soil:						
Control	23.0	10.1 c	1.5	1.2 e	2.1	1.3 f
SM_{40}	24.3	10.7 b	1.8	1.4 d	2.6	1.7 e
SM_{80}	24.9	11.6 b	2.5	2.3 b	3.8	3.1 c
SM_{120}	25.4	12.8 a	2.9	2.5 b	4.1	3.6 b
SM_{160}	26.3	13.5 a	3.2	2.8 a	4.8	4.2 a
G_{40}	23.4	10.6 b	1.6	1.3 d	2.5	2.1 e
G_{80}	23.9	11.2 b	1.8	1.5 d	2.8	2.5 d
G_{120}	24.5	11.8 b	2.6	2.1 c	3.3	2.8 c
G_{160}	25.2	12.4 ab	2.9	2.5 b	3.6	3 c
LSD (5%)	–	1.3	–	0.26	–	0.4
SM-IOC (%)	9.67	20.3	73.33	87.5	82.14	142.31
G-IOC (%)	5.43	13.86	48.33	54.17	45.24	96.15

¶In a columns 110 DT of N, P and S; categorized class (a, b, c, d, e and f) is shown. A common letter means the values do not differ significantly at 5 % level by LSD according to DNMRT (Duncan's New Multiple Range Test)
†IOC = Increased over control and DT = days after transplanting.

of the studied soils.

Moreover, the removal of SM from the ASSs will reclaim these acute problem soils. Massive fish kills in the water bodies polluted by toxic elements drained from the ASSs have been widely reported in the world (Callinan *et al.*, 1993; Lin and Melville, 1994). Losses due to fish killing from such situation in the coastal plains of Bangladesh were about US$ 3.4 million during 1988-89 (Callinan *et al.*, 1993). From the 0.7 M ha of ASSs in the coastal plains of Bangladesh, the SM can be obtained from the soils at depth of about 10 to 80 cm (Khan, 2000). The reclamation of these soil materials may be difficult but essential due to the presence of high acidity and salinity during the dry periods of the year, which not only hinders crop growth but also destroys aquatic organisms (Khan *et al.*, 2006). But the SM of high acidity and salinity will not harmful for soils and crops might be due to dilution effects as observed in the present study. However, the use of SM should be done in the soils of pH >5.5 in consideration with the high acidity and associated element dynamics of ASSs.

To our knowledge, there are no reports available that present the use of SM as sulfur fertilizer for the production of rice. Some observations of sulfur fertilizations on the growth and yield of crops in sulfur deficient soils were reported by some researchers. Among them, Sremannarayana *et al.* (1995) worked on the effects of sulfur fertilization (gypsum, $MgSO_4$, $(NH_4)_2SO_4$ and elemental sulfur) at the rates of 0, 20, 40 and 60 kg ha^{-1} on yield and quality of sunflower and stated that both seed and stalk yields significantly increased with increased rates of sulfur irrespective of sources of sulfur used. Khan *et al.* (2002, 2007) had reported that the growth, yield, and nutrition of tomato, onion and sunflower were strikingly increased by the application of SM compared with gypsum and $MgSO_4$. The application of SM not only increased the sulfur uptake by crops but also enriched the S and organic matter status of the soils. They also revealed that the application of SM had pronounced residual effects not only on crop yields but also on the organic matter and sulfur status of the soils during subsequent trails.

4. Conclusion

The application of SM and gypsum increased the average grain yield by 76 to 78% and 37 to 46% IOC, available sulfur by 228 to 140% and 88 to 187%, respectively, in both the soils, suggesting that the SM compared with gypsum as a source of sulfur fertilizer was potential and effective for the recovery of sulfur deficiency, improvement of nutrition of rice and fertility status of the soils. However, further field research is essential. The high organic matter (4%), available S (24. c mol kg^{-1}) and total S (166 c mol kg^{-1}), and high Mg and other nutrient contents of the SM deserve attention to use these soil materials for the reclamation of poor soils like saline, alkaline, calcareous, and sulfur deficient soils. The use of SM by removing from acid sulfate soils will not only lead the soils be reclaimed permanently but also safe the surrounding ecosystems of the ASSs from their severe effects. The use of SM had no adverse effects on the rice and soils. Hence, immediate steps should be taken to consider these ASSs or SM as they have dual benefits, use as sulfur fertilizer as well as for reclamation of the ASSs.

Acknowledgements

The study was carried out under the financial and technical support (1998-2005) of the Volkswagen (Ref: 1/73 802, dated 03-08-98) and the Alexander von Humboldt (AvH) foundations, respectively.

References

Balsa, M.E., Serrao, M.G., Martins, M.I.M., Castelo-Branco, M.A., Gusmao, M.R. and Fernandes, M.L. 1996. Effects of pyrite residue amendment on sulfur availability in a calcareous soil cropped with sown pasture. In Fertilizers and Environment C. Rodriguez-Barrueco, editor. Kluwer academic Publ., Printed in the Netherlands, pp 453-455.

BARC (Bangladesh Agriculture Research Council). 1997. Fertilizer Recommendation Guide. Publ. BARC, Farm gate, Tejgaon, Dhaka Bangladesh.

Black, C.A. 1965. Methods of Soil Analysis, Part 2, Series 9, 894-1372, American Society of Agronomy, Inst. Publ., Madison, WI.

Callinan, R.B., Fraser, G.C., Melville, M.D. 1993. Seasonally recurrent fish mortalities and ulcerative disease out breaks associated with acid sulfate soils in Australia estuaries. In: Selected Papers of the Ho Chi Minh City Symposium on Acid Sulfate Soils. D.L. Dent and M.E.F. van Mensvoort, editors. Pub. 53, Int. Inst. for Land Reclamation and Improvement, Wageningen, The Netherlands, pp 403-410.

Chapman, H.D. 1965. Cation exchange capacity. *In* Methods of Soil Analysis. Part 2, C.A. Black, editor. Agronomy Series 9; American Society of Agronomy, Publ. Madison, WI, U.S.A. pp 891-900.

Day, P.R. 1965. Particle fractionation and particle size analysis. *In* Methods of Soil Analysis. Part 2, C. A. Black, editor. Agronomy Series 9; American Society of Agronomy, Publ. Madison, WI, U.S.A. pp. 545-566.

Eriksen, J., Thorup-Christensen, K. and Askegard, M. 2004. Plant availability of catch crop sulfur following spring incorporation. Journal of Plant Nutrition and Soil Science 167, 609–615.

Girma, K., Mosali, J., Freeman, K.W., Raun, W.R., Martin, K.L. and Thomason, W.E. 2005. Forage and grain yield response to applied sulfur in winter wheat as influenced by source and rate. Journal of Plant Nutrition 28, 1541–1553.

Hesse, P.R. 1971. A text Book of Soil Chemical Analysis, John Murry Publ., London.

Jackson, M.L. 1973: Soil Chemical Analysis, Prentice Hall of India Pvt. Ltd., New Delhi. pp 41-330.

Khan, H.R., Bhuiyan, M.M.A., Kabir, S.M., Blume, H-P., Oki, Y. and Adachi, T. 2007. Consequences of basic slag on soil pH, calcium and magnesium status in acid sulfate soils under various water contents. Journal of Biological Science 7, 896-903.

Khan, H.R., Bhuiyan, M.M.A., Kabir, S.M., Oki, Y., Adachi, T. 2006. Effects of selected treatments on the production of rice in acid sulfate soils in a simulation study. Japanese Journal of Tropical Agriculture 50(3), 109-115.

Khan, H.R., Rahman, M.K., Rouf, A.J.M.A. and Satter, G.S. 2003. Consequences of microbial biomass and organic carbon in burnt and unburnt soil profiles in different agro-ecological zones in the western part of Bangladesh. Bangladesh Journal of Soil Science, 27-29, 51-60.

Khan, H.R., Bhuiyan, M.M.A., Kabir, S.M., Ahmed, F., Syeed, S.M.A. and Blume H.P. 2002. The assessment and management of acid sulfate soils in Bangladesh in relation to crop production, Chapter 22, In The restoration and management of derelict land: Modern approaches. M.H. Wong and A.D. Bradshaw, editors. pp 254-263; World Scientific, www.worldscientific.com

Khan, H.R. 2000. Problem, prospects and future directions of acid sulfate soils. In Proceedings of International Conference on Remade Lands 2000, Ed. Brion, A. and R.W. Bell; Nov. 30 to Dec. 2, 2000, Perth, Australia, pp 66-67.

Khan, H.R. and Adachi, T. 1999. Effects of selected natural factors on soil pH and element dynamics studied in columns of pyretic sediments. Soil Science and Plant Nutrition, 45, 783-793.

Khan, H.R., Rahman, S., Hussain, M.S. and Adachi, T. 1994. Growth and yield response of rice to selected amendments in an acid sulfate soil. Soil Science and Plant Nutrition, 40, 231-242.

Lin, C. and Melville, M.D. 1994. Acid sulfate soil-landscape relationships in the Pearl River Delta, southern China. Catena. 22, 105-120.

Mascagni, H.J.Jr., Harrison, S.A. and Padgett, G.B. 2008. Influence of sulfur fertility on wheat yield performance on alluvial and upland soils. Communications in Soil Science and Plant Analysis, 39, 2133–2145.

Ming Xian FAN and MESSICK Donald L. 2007. Correcting Sulphur Deficiency for Higher Productivity and Fertilizer Efficiency, IFA crossroads, Asia-Pacific 2007, 17-19 December Bail, Indonesia.

Ming Xian FAN, 2007. Correcting Sulphur Deficiency for Higher Productivity and Fertilizer Efficiency, IFA crossroads, Asia-Pacific 2007, 17-19 December Bail, Indonesia .

Nelson, D.W. and Sommers, L.E. 1982. Total carbon, organic carbon and organic matter. In Methods of Soil Analysis. Part 2, Ed. A. L. Page, Agronomy Series 9, American Society of Agronomy, Publ. Madison, WI, U.S.A. pp 539-579.

Olsen, S.R., Cale, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. United States Department of Agriculture Circ. 939, Washington, USA.

Orndorff, Z. and Daniels, W.L. 2002. Delineation and management of sulfidic materials in Virginia highway corridors. Final report to the Virginia transportation research council, Charlottesville, Virginia, Sept. 2002, VTRC 03-CR3.

Richards, L.A. 1954. Diagnosis and improvement of saline and alkali soils. In United States Department of Agriculture Handbook No. 60; US Govt. Print. Office, Washington, U.S.A. pp 84-156.

Sakai, H. 1978. Some analytical results of sulphur deficient plants, soil and water. Workshop on sulfur nutrition in rice, December, BRRI, Publication No. 41, pp 35-59.

Scherer, H.W. 2001. Sulphur in crop production – invited paper. European Journal of Agronomy, 14, 81–111.

Schonhof, I., Blankenburg, D., Müller, S., Krumbein, A. 2007. Sulfur and nitrogen supply influence growth, product appearance, and glucosinolate concentration of broccoli. Journal of Plant Nutrition and Soil Science, 170, 65–72.

SRDI (Soil Resources Development Institute). 1999. Map of the nutrient status of sulfur and upazila land soil resource utilization guide.

Sremannarayana, B. Raju, A., Satyanarayana, S. 1995. Effects of sulfur on yield and quality of sunflower. Journal of Maharashtra Agricultural Universities, 20 (1), 63-65.

Tiwari, K.N., Dwivedi, B.S. and Pathak, A.N. 1985. Iron pyrites as sulfur fertilizer for legumes. Plant Soil, 86, 295-298.

Zaman, S.M.H., Rahman, K. and Howlader, M. 1982. Simple lessons from biometry. Publ. No. 54, Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh.