Sulfur Nutrition and Diagnosis of Sulfur Deficiency of Rice Plants

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As an essential nutrient element for growth, sulfur is required by plants in amounts comparable to phosphorus. In industrial areas, on the other hand, a high concentration of sulfur dioxide causes damages to plants, but it is also proved that atmospheric sulfur is directly absorbed by plants through stomatal openings. According to Yamazoe[8], however, stomatal absorption of sulfur accounted for only 1.9–11.5% of the total leaf sulfur after fumigation with sulfur dioxide of crops for several days. Evidently, the absorption from the soil is the main route of the sulfur nutrition of plants.

While there are few instances, including those reported by Otsuka[5] on serpentine soils, of the deficiency of sulfur on arable land in Japan, a number of reports have been published from Australia, New Zealand, the United States, Canada, and South America, though all of them dealt with the deficiency of this element in upland crops. Recently, however, the occurrence of sulfur deficiency in lowland rice was reported in Java by Ismunadji et al.[3]

To date, information on the sulfur nutritional status of rice plants seems too meager to assess the need of application of sulfur-containing fertilizers to paddy field. In this article are given some of the experimental results obtained at National Institute of Agricultural Sciences[6].

Sulfur deficiency symptoms of rice plants

Symptoms of sulfur deficiency differ with different species of plants. Most of the plants tested in our water culture experiments, including rice, wheat, rye, maize, soybean, sunflower, cucumber, and tomato became chlorotic when deficient in sulfur, but onion and cruciferous plants such as raddish and mustard gave only reduced growth without showing discoloration in leaves. Generally, in the former group of plant species sulfur deficiency was characterized by more conspicuous loss of chlorophyll in upper leaves with milder influence on the expansion of leaves than the deficiency in nitrogen.

In the case of rice plants, however, it was most difficult to distinguish between sulfur and nitrogen deficiencies only by the visual symptoms, because they closely resembled each other in appearance. Sulfur-deficient rice plants could be easily mistaken for those deficient in nitrogen.

A sulfur deficiency symptom of rice plants appears initially on leaf-sheaths, which become yellowish. Then, the yellowing proceeds to leaf-blades and the whole plant becomes chlorotic at tillering stage. The plant is reduced both in height and the number of tillers, but roots tend to elongate in the same way as nitrogen deficiency. As shown in Table 1, the decrease in dry weight was greater in leaf-blades than stems and roots, which indicates that sulfur gave more

Table 1. Growth of rice plants influenced by sulfur deficiency (water culture)

Date	Plant height (cm)	No. of tillers per hill	Root length (cm)	Dry wt (g/hill)			Ear length (cm)	No. of grains per ear	1000-grain wt (g)
				Leaf blade	Stem	Root			
				Control					
June 12	59.1	11.3	—	1.1	1.1	0.5	—	—	—
July 1	84.9	31.1	48.5	7.1	6.2	1.7	—	—	—
Aug. 2	109.9	34.8	53.4	17.4	38.9	4.5	—	—	—
Sep. 17	78.3*	36.8*	—	16.3	51.6	5.2	18.2	75.7	17.0
				S deficiency					
June 12	54.8	10.3	—	1.0	1.1	0.6	—	—	—
July 1	62.0	13.5	59.5	2.9	5.3	1.8	—	—	—
Aug. 2	81.4	12.8	62.5	5.4	16.5	2.7	—	—	—
Sep. 17	55.0*	15.0*	—	6.1	24.4	3.4	15.3	52.4	16.0

Flowering: Aug. 2, harvest: Sept. 17.
Figures with asterisk (*) denote culm length and number of ears, respectively.

pronounced influences on the growth of leaves than other organs. At maturity, they gave short ears, reduced number of ears per plant, and reduced number of grains per ear.

Measurement of available sulfur in soil

As a means of evaluating the available sulfur status in soil, the A value method seems to be advantageous for the following reasons. Firstly, the A value will not change if the amount of available sulfur and the availability of the sulfur standard applied were not changed, even when the growth of the plant is affected by environmental changes. So, the experimental errors due to plant-top environments could be minimized. Secondly, the measurement can be made without nutrient stress. But since the A value technique has a limitation in general use in that it requires facilities for handling radioisotopes, proper methods comparable to the A value technique merit study.

Thirty-one lowland rice soils and seven upland soils were taken from surface layers in the fields of experiment stations at various locations in Japan. They were placed in 1.5-liter pots, saturated with water and fertilized, besides NPK, with $^{35}S\text{-}H_2SO_4$ enriched sodium sulfate which was mixed thoroughly with the entire soil. Seedlings of rice plants, var. Norin 29 at the 3-leaf stage, which had been raised in deionized water were transplanted and grown for 40 days in a greenhouse. Watering the pots was done with deionized water throughout the experiment. After harvesting, plant tops were analyzed for sulfur contents as barium sulfate, the radioactivity was measured by a GM-counter, and sulfur A value of the soil was determined.

Extraction of soil was performed with KH_2PO_4 solution (500 ppm P) or 0.03*M* $Ca(H_2PO_4)_2$ solution at the soil: solution ratio of 1 : 5. Calcium dihydrogenphosphate at the strength of 0.03*M* was employed here, because it was revealed in a preliminary trial that volcanic ash soil showed an increase in extractable sulfur content with the increase in the concentration of $Ca(H_2PO_4)_2$ up to this value. The extracted sulfur and the total sulfur contents of soil were determined by Johnson and Nishita's distillation method[4].

Results are given in Table 2. One can notice high correlation coefficients between the A value and the soil sulfur fraction extracted with either KH_2PO_4 (r=0.897**) or $Ca(H_2PO_4)_2$ (r=0.912**). It may be concluded from these results that the extraction with phosphate solutions can be used as effectively

Table 2. Correlations between sulfur A value and sulfur fractions of soil

Sulfur fractions of soil	Regression equation	Correlation coefficient
A value (x), KH_2PO_4-extractable S (y)	$y=2.06x-107.37$	0.897** (n=38)
A value (x), $Ca(H_2PO_4)_2$-extractable S (y)	$y=1.93x-97.09$	0.912** (n=38)
A value (x), total S (y)	$y=4.78x+290.31$	0.652** (n=26)
Total S (x), KH_2PO_4-extractable S (y)	$y=0.22x-47.52$	0.715** (n=26)
Total S (x), $Ca(H_2PO_4)_2$-extractable S (y)	$y=0.21x-44.19$	0.737** (n=26)

** Significant at 1% level, n: Number of samples

Table 3. Correlation coefficients between soil sulfur contents and sulfur concentrations in various parts of rice plants

Soil sulfur fractions	Leaf-blade	Leaf-sheath	Culm	Whole straw	(No. of samples)
		Minus-S and plus-S plots combined			
A-value	0.444*	0.608**	0.666**	0.605**	(n=23)
KH_2PO_4-extractable S	0.219	0.318	0.355	0.312	(n=23)
$Ca(H_2PO_4)_2$-extractable S	0.205	0.320	0.362	0.313	(n=23)
Total S	0.088	0.063	0.193	0.128	(n=21)
		Minus-S plots			
A-value	0.690*	0.783*	0.786*	0.772*	(n= 8)
KH_2PO_4-extractable S	0.636	0.725*	0.739*	0.713*	(n= 8)
$Ca(H_2PO_4)_2$-extractable S	0.621	0.719*	0.735*	0.707*	(n= 8)
Total S	0.285	0.316	0.414	0.328	(n= 7)
		Plus-S plots			
A-value	0.341	0.535*	0.632**	0.550*	(n=15)
KH_2PO_4-extractable S	0.066	0.214	0.260	0.200	(n=15)
$Ca(H_2PO_4)_2$-extractable S	0.037	0.213	0.264	0.195	(n=15)
Total S	−0.116	−0.038	0.095	−0.002	(n=14)

Asterisks: Significant at 1% (**) and 5% (*) levels.

as the A value method for the estimation of available sulfur contents of lowland rice soils, though the phosphate extractants were originally proposed for upland soils by Ensminger[2] and Barrow[1].

Soil sulfur vs. sulfur status of rice plants

In practice, however, it is important to know whether and to what extent the soil sulfur fraction measured as above could reflect the sulfur nutritional status of rice plants grown in the field.

Table 3 gives correlation coefficients between soil sulfur contents and sulfur concentrations in the straw of rice plants sampled from fields at maturity. The correlation coefficients were obtained within the group of rice plants that received sulfur-containing NPK fertilizers (plus-sulfate plots) and within the group that received no fertilizers and hence no sulfates (minus-sulfate plots).

Sulfur A values were correlated at significant levels, not only for minus-sulfate plots but for plus-sulfate plots as well, with sulfur concentrations in the leaf-sheaths, culms, and the whole straw of rice plants. Soil sulfur fractions extracted with phosphates were also found to be correlated at a significant level with sulfur concentrations in the leaf-sheaths, culms, and the whole straw of rice plants grown on the minus-sulfate plots. But no close correlations were found between the total sulfur contents of soil and the sulfur concentrations in rice plants.

The results obtained here indicate that the extraction of soil with the phosphate solution could be a useful method for the evaluation of sulfur supplying power of lowland rice soils. Practically, there was no difference in the magnitude of correlation coefficients between potassium and calcium dihydrogenphosphates. But calcium phosphate is reported to be more advantageous on certain soils in filtrating the soil solution with much ease. As for the plant parts, since the sulfur concentrations in the leaf-blades gave no close correlations with the extracted sulfur contents of soil, analysis should be made either on the whole straw, leaf-sheaths, or more preferably on culms which gave the highest correlation coefficient among plant parts.

Critical levels of sulfur

Lowland rice fields so far studied in Japan are mostly rich in available sulfur as shown in Table 4. Humic volcanic ash soils, peaty soils, and marine polder soils have high contents of phosphate-extractable sulfur, while sandy soils derived from granite generally low. After his survey on grassland soils, Tsuji[7] also found high concentrations of sulfur in humic volcanic ash soils, most of which contained more than 0.1% total sulfur.

In Table 4, two granitic sandy soils of minus-sulfate plots which gave the lowest concentrations of available sulfur of 7–11 ppm are the soils from Hiroshima and Hyogo Prefectures. In a greenhouse experiment, rice plants were apparently responsive to the application of sulfate on these two soils. Also, field trials at Hiroshima Agricultural Experiment Station have shown that the yields of both grain and straw of rice plants are a little higher almost every year on the plus-sulfate plot than on the minus-sulfate plots. The sulfur concentrations of the whole straw of rice plants at maturity were 0.06% and 0.05% on Hyogo and Hiroshima soils, respectively. These values were fairly below the average sulfur concentration of 0.081% in the straw of twenty-three samples taken from various locations in Japan.

It could be inferred from these results that the critical concentrations of sulfur should be 7–11 ppm in the soil as phosphate-extractable sulfur and 0.05% in the straw at maturity. Below these concentrations, rice plants will be responsive to the application of sulfate.

In another experiment, thirty-day old seedlings of rice plants, var. Nihonbare, were transplanted in pots and grown by means of water culture at varied rates of sodium sulfate added in the nutrient solution. At tillering stage, thirty-six days after transplanting, they were harvested and determined for dry weight and concentration of sulfur. Fig. 1 illustrates relationships between the concentration of sulfur in the shoot and the dry weight of

Table 4. Available sulfur contents of soils estimated by extraction with 0.03 *M* calcium dihydrogen-phosphate, ppm S.

Soils	Plus-sulfate plot	Minus-sulfate plot
Sandy Soils derived from granite, lowland rice	9– 37 (3)*	7– 11 (2)*
Alluvial soils, lowland rice	32– 78 (10)	22– 27 (5)
Humic volcanic ash soils, lowland rice	41–289 (4)	—
Humic volcanic ash soils, upland crops	572–637 (3)	110–510 (2)
Peaty soils, lowland rice	525 (1)	183 (1)
Marine polder soils, lowland rice	339 (1)	—
Nishigahara subsoil, industrial area	—	309 (1)

*: Figures in parentheses indicate number of samples.

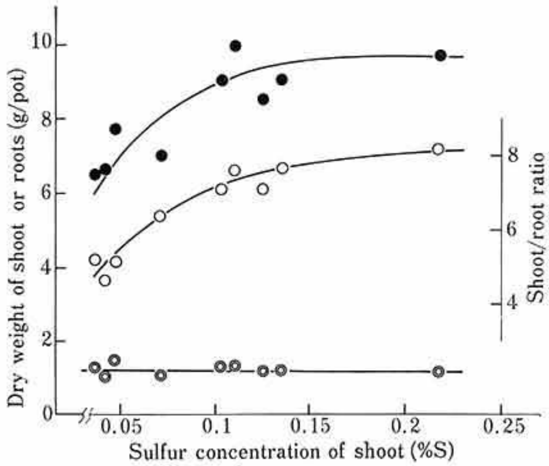

Fig. 1. Relationships between sulfur concentration in the shoot and dry weight of shoot and roots of the rice plant at tillering stage

shoots and roots. Below 0.10% sulfur in the shoot, the dry weight of shoot and the shoot/root ratio decreased considerably, though the weight of roots remained unchanged. Therefore, 0.10% sulfur concentration in the shoot could be taken as a criterion for the assessment of the need of sulfur application at tillering stage of rice plants.

Conclusions

Criteria for the diagnosis of sulfur nutritional status of lowland rice are proposed here. Extraction with phosphate was proved to be a simple but useful method for evaluating the fertility of paddy soils with respect to available sulfur. However, the correlation coefficients between the soil sulfur fractions extracted with phosphates and the sulfur concentrations of rice plants grown in fields were found to be around 0.71 (significant at 5% level), the value that is not high enough to a satisfactory degree. Studies are needed to develop a new method that will give a higher correlation coefficient and particularly be suited to lowland rice soils. For this purpose, the transformation of sulfur in the rhizosphere in relation to oxidation-reduction reactions and the mechanism of intake of sulfur by the roots of rice plants merit study.

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