ELEMENTAL SULFUR COATED FERTILIZER MATERIALS AS SULFUR SOURCES FOR RICE UNDER FLOODED AND NON-FLOODED CONDITIONS

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ABSTRACT

A study was undertaken to investigate the effectiveness of a range of elemental sulfur (S^0) coated TSP fertilizer materials in rice under flooded and non-flooded conditions.

The experiment was conducted in a glasshouse at the University of New England, Armidale, N.S.W., Australia, using a factorial combination of 6 sources of S^0 coated fertilizer materials [Gold-phos 10 (GP10), UNE511, UNE1, TSP+S^0f (fine), TSP+S^0m (medium), TSP+S^0c (coarse)], and a Control, 2 water regimes and 3 replications. The soil used in the study was an S-deficient Aquic Haplustalf. The treatments were arranged in a randomized complete Block design (RCBD). P and S from the different S^0 coated materials were applied at the rates of 46 kg P/ha and 10 kg S/ha, respectively.

The use of ^{35}S labeled soil and the employment of the Reverse Dilution Technique enabled the estimation of the recovery of the fertilizer S in the various components derived from the different S sources.

Mean percentage recovery of fertilizer S in the straw and grain, and mean total S recovered in the rice tops were significantly lower in the GP10 and UNE511 fertilizer treatments.

Based on the results, it was concluded that UNE1, TSP+S^0f, TSP+S^0m and TSP+S^0c were effective S sources for rice under flooded and non-flooded conditions.

Keywords: *elemental S, rice, coated fertilizers, radioactive S, tiller, grain.*

INTRODUCTION

Sulfur (S) is one of the major nutrients required by plants for their growth. It is a major constituent of the amino acids – cysteine and methionine, and various other compounds in plants (Russell 1973; Anderson 1975; Thomson *et al.* 1986).

Despite its importance as an essential plant nutrient, it has received little attention compared to nitrogen (N), phosphorus (P) and potassium (K) and only in the recent past, has its significance been recognized. The incidence of S deficiency is becoming widespread and has now been widely recognized in many countries (Morris 1987). S deficiency is widespread in most rice growing regions, particularly in Southeast Asia (Blair 1983; Ismunadji *et al.* 1983; Mamaril *et al.* 1983; Hoult *et al.* 1983), Latin America (Wang *et al.* 1976), and Africa (Osiname and Kang 1975).

In the past, the so-called "low analysis" fertilizers such as single superphosphate and ammonium sulfate were the principal sources of S for most agricultural crops. Recently, however, there has been a growing shift away from the use of these fertilizers to the so-called "high analysis" fertilizers such as urea, triple superphosphate (TSP), mono- and di- ammonium phosphates which contain little or no S (Blair 1979; Morris 1987).

As the need for S increases to counter the S deficiencies resulting from the use of high analysis fertilizers, many attempts have been made to use elemental S (S^0) to supply crop demand (Fisher *et al.* 1984). However, since plants use only SO_4^{2-} - S, S^0 needs to be oxidized before a plant can utilize the S. Coating of fertilizer materials with S^0 has been introduced to deliberately supply S to plants and this employ finely ground S^0 to granular products with various binders such as lignosulfonate, formaldehyde, etc. Most of these materials contain 10 – 100 % S (Tandon 1987).

The experiment was conducted under glasshouse conditions to investigate the effectiveness of some

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of the S^0 – coated TSP fertilizer materials as S sources for rice in terms of yield, S content and the recovery of fertilizer S in the straw and grain components, under flooded and non-flooded conditions.

MATERIALS AND METHODS

Location

The experiment was conducted from January to May 1997 in a glasshouse at the Department of Agronomy and Soil Science of the University of New England, Armidale, N.S.W. Australia.

Experimental Design

The experiment consisted of a factorial combination of 6 S^0 coated fertilizer materials [Gold-phos 10 (GP10), UNE511, UNE1, TSP+S^0f (fine), TSP+S^0m (medium), TSP+S^0c (coarse)], and a Control, 2 water regimes (flooded and non-flooded) and 3 replications. These treatments were arranged in a randomized complete block design (RCBD).

Soil Sampling and Preparation

Surface layer (0-15 cm) of an S-deficient Aquic Haplustalf (Anderson, 1988; Dana, 1992) soil from Uralla, N.S.W., was collected from a natural pasture site, air-dried, processed through a soil shredder and passed through a 2 mm sieve to obtain a uniform soil particle size, before being used in the experiment.

Coating of TSP Granules with Elemental S

Three different S^0 particle sizes were used to coat the TSP granules. These included 53-154 µm (fine), 154-263 µm (medium) and 263-328 µm (coarse). Coating of TSP granules with S^0 was done by weighing 20g each of the three S^0 particle sizes and mixing them thoroughly with 10 ml of calcium lignosulfonate to make a paste. TSP granules of 2-2.8 mm diameter were then added to the S^0/lignosulfonate mixture and mixed thoroughly with a glass rod. To get a good coated material, the mixture was transferred to a rotating drum and a slightly warm air blown over the granules. The S^0 coated TSP materials with the 3 different particle sizes were then air-dried and stored in three different plastic jars.

Measurement of the S content of each of the coated materials was done by using the Combined Phosphorus and Sulfur Digest Method for Soils and Fertilizers by Till *et al.* (1984). The P and S rates used in the experiment (46 kg P/ha and 10 kg S/ha) were thus calculated based on the P and S contents of the coated TSP materials as obtained from the analysis and the surface area of the pots (183 cm^2).

^{35}S Labeling of the Soil Samples

Prior to potting, 42 lots of 1.85 kg of soil were weighed and put in plastic bags. ^{35}S was then used to labeled the soil samples. This was done by using a syringe to apply 5 ml of the radioactive solution ($K_2{}^{35}SO_4$) to the soil surface in the bags. Immediately after the application of the radioactive solution, 50 ml of deionized water was added and mixed thoroughly with the soil in the plastic bags. The labeled soil samples were then kept in a storage room to incubate for 3 weeks. Incubation allows the equilibration of ^{35}S with the native sulfate and rapidly turning over organic S in the soil (Dana, 1992). After the incubation period, the sample in the plastic bag was placed inside a second plastic bag so that there were two plastic bags/pot as inner linings. These were then transferred to the glasshouse, manually irrigated with deionized water to field capacity and were ready for basal nutrients application, which was done a day later.

Basal Nutrients and Treatment Applications

Only N and K were applied as basal nutrients and these were mixed thoroughly with the soils. The nutrients were applied as Urea (400 mg urea/pot) and KCl (35.2 mg KCl/pot), respectively. A day after the basal applications, 6 two weeks old rice (variety IR30) seedlings which were grown in quartz sand were transplanted per pot.

After the adjustment period of 1 week, 6 different S^0 coated TSP fertilizer materials and 2 water regimes (flooded and non-flooded) were applied. The 6 different coated TSP fertilizer materials include Gold-phos 10 (GP10), UNE511, UNE1, TSP+S^0f, TSP+S^0m and TSP+S^0c. Description of the coated TSP material UNE1 is given by Dana *et al.* (1994a). UNE511 was made in a similar manner as UNE1, but its coat was hardened during the drying process. Golphos 10 is a commercial S^0 coated TSP fertilizer which contains 18 % P and 10 % S. It is manufactured by Hi-Fert Pty Ltd, Australia. For the latter three S^0 coated TSP, refer to the section on coating of TSP granules above.

All these S^0 coated fertilizer materials were applied by placing the granules uniformly on the soil surface. The flooded treatments were imposed by adding deionized water to a level of 4 cm above the soil surface and maintained at that level until the ripening period when watering was terminated. For the non-flooded treatments, watering was maintained at or near field capacity by weighing until the ripening period when watering ceased. Table 1 indicates the

Table 1. **Application rates (mg/pot) of P and S of the elemental S coated fertilizer materials.**

Coated material	% P	% S	Coated TSP mg/pot for 10 kg S/ha	P added in coated TSP (mg/pot)	Extra P needed to make 84.18 mg/pot for 46 kg P/ha	Uncoated TSP to make up P level (mg/pot)
GP10	18.0	10.0	183.0	32.9	51.2	222.5
UNE511	17.4	9.7	189.0	32.9	51.2	222.5
UNE1	20.0	10.0	183.0	36.6	47.6	206.6
TSP+S^0f (53-154μm)	20.7	10.3	177.5	36.7	47.5	206.2
TSP+S^0m (154-263μm)	20.3	11.3	162.1	33.0	51.2	222.5
TSP+S^0c (263-328μm)	20.3	11.6	158.2	32.0	52.2	226.2

application rates of P and S of the S^0 coated fertilizer materials.

Tiller Count and Leaf Sampling

Twenty days after transplanting (DAT), the first tiller count was made and at 27 DAT, a second tiller count was carried out and repeated at 2 weeks intervals. The first leaf sampling was made during the second tiller count (27 DAT) with the subsequent tiller counts and leaf samplings carried out at 41 DAT, 55 DAT and 69 DAT. Hence, a total of 5 tiller counts and 4 leaf samplings were conducted.

To sample the leaves, the first step was to dry the digestion bottles (50 ml borosilicate screw-top) without the caps, in an oven at 80 °C for 24 hours. After cooling, the dry bottles were weighed and taken to the glasshouse.

Sampling of the leaves for each treatment was done by clipping at the leaf base, the youngest fully expanded leaf from the top of the main tiller with a pair of scissors. Since there were 6 rice plants/pot, leaves were sampled from the first three plants and at the next sampling, the samples were taken from the other three plants, alternating at the subsequent samplings.

Immediately after the leaves were harvested, they were cut into small pieces of about 5 mm in length and put in the appropriate digestion bottles. The bottles with the fresh leaves samples were then taken to the laboratory and their fresh weights taken. These were then dried in the oven at 80 °C for 48 hours. After cooling, the bottles with the dry samples were weighed to determine the dry sample weights for each treatment.

Panicle, Grain and Straw Harvest

At harvest, the number of productive panicles were counted and recorded. The grains were harvested by stripping them from the panicles and sorted out into filled and unfilled grains. These were counted and recorded. The straw was harvested by cutting approximately 1 cm above the soil. The unfilled and filled grains, and straw were then dried at the oven at 80 °C for 48 hours and weighed after cooling. Each straw and filled grain sample was then ground to pass a 1 mm screen.

Laboratory Analyses

Laboratory analyses of the leaf samples for each harvest was done following the procedures outlined by Anderson and Henderson (1986) for Sealed Chamber Digest for P, S, K, Na, Mg, Ca and trace elements determination. Total S in the leaves for each sampling times (27 DAT, 41 DAT, 55 DAT and 69 DAT), was measured by the ICP spectrometry (ICP-AES) and ^{35}S content was measured by Liquid Scintillation Counting (Till *et al.* 1984). The Reverse Dilution Technique of Shedley *et al.* (1979) was used to calculate the recovery of fertilizer S by the rice plants whereby the radioactivity data were converted to specific radioactivity ratio (SRR). SRR is the ratio of the treatment to the Control specific radioactivity (SR) and SR is the activity of ^{35}S in becquerel per gram of dry matter (Bq/g DM) expressed per unit of total S content of the plant leaves (μg/g). Therefore, the amounts of sulfur derived from the fertilizers were estimated as (1-SRR) x 100%.

For analysis of total S in the straw and grain, a sub-sample of 0.20 g for each treatment and plant component was taken and digested using the same procedure as outlined for leaf analyses, and measured by ICP Spectrometry. ^{35}S content was measured by Liquid Scintillation Counting (Till *et al.* 1984) and fertilizer S recovery was calculated using the Reverse Dilution Technique of Shedley *et al.* (1979).

Statistical Analysis of Data

The data collected for the different parameters measured were analyzed by the analysis of variance (ANOVA) using the NEVA Version 3.3 computer program (Burr, 1982). Mean separation for each treatment was determined using the Duncan's Multiple Range Test (DMRT), where treatment effects observed at the probability level of 5% or less are treated as significant.

RESULTS

Yield Components

(i) Tiller numbers

The effects of the different S^0 coated fertilizer sources on tiller numbers were significant at 20 and 27 DAT (Table 2). At 20 DAT, higher tiller numbers were observed in the TSP+S^0f, TSP+S^0m, TSP+S^0c, UNE1 and UNE511 S^0 fertilizer sources, which were similar.

At 27 DAT, application of UNE511 resulted in a significantly lower tiller numbers, which was similar to the Control treatment. No significant differences in tiller numbers were observed between the different S^0 coated fertilizer sources at 55 and 69 DAT.

There were significant differences in tiller numbers observed at different counting times (Figure 1). At 20 DAT, the tiller numbers produced in the non-flooded treatment was significantly lower than that of the flooded treatment. The highest tiller numbers produced in the flooded treatment was observed at 27 DAT, although this was similar to the non-flooded treatment with the means of 3.84 and 3.98 tillers/plant for the non-flooded and flooded treatments, respectively. At 69 DAT, the till numbers under flooding, declined dramatically as compared to the tiller numbers under non-flooding. Figure 1 also shows that tiller numbers under flooding were consistently lower after the second tiller count (27 DAT) compared to the non-flooded treatment.

(ii) Filled grain numbers

There was no significant water regime x S^0 fertilizer source interaction (Appendix 1) on the number of filled grains. However, the application of the different S^0 fertilizer sources resulted in significant differences in the mean number of filled grains (Table 3). The mean filled grain numbers in the Control and GP10 treatments were similar but significantly lower as compared to the mean filled grain numbers in the other S^0 fertilizer sources.

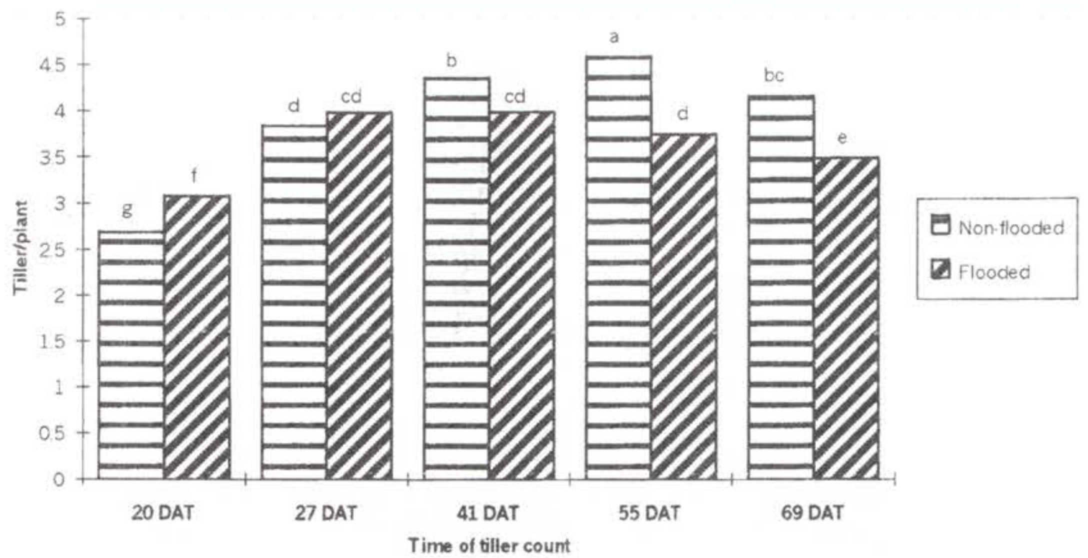
No significant differences in mean filled grain numbers were recorded in the UNE1, TSP+S^0f, TSP+S^0m and TSP+S^0c, and between UNE511, UNE1 and TSP+S^0f S^0 fertilizer sources (Table 3). Application of the different S^0 coated fertilizer sources did not have any significant effects on the number of unfilled grains, and panicle numbers were neither

Table 2. **Tiller numbers (tiller/plant) counted at different times as influenced by different S fertilizer sources.**

	S^0 coated fertilizer materials						
Harvest time	Control	GP10	UNE511	UNE1	TSP+S^0f	TSP+S^0m	TSP+S^0c
20 DAT	2.2 c	2.8 b	2.9 ab	3.0 ab	3.2 a	3.0 ab	3.0 ab
27 DAT	3.2 c	4.2 a	3.4 c	4.1 ab	3.9 ab	4.1 ab	3.8 ab
41 DAT	3.6 b	4.1 a	4.2 a	4.4 a	4.3 a	4.2 a	4.4 a
55 DAT	3.9 b	4.1 ab	4.1 ab	4.2 ab	4.4 a	4.2 ab	4.2 ab
69 DAT	3.8 a	3.5 a	3.8 a	3.9 a	4.0 a	3.8 a	3.9 a

Numbers followed by the same letter in a row within each harvest time do not differ significantly at the 5% level by DMRT.

***Figure 1.* Tiller numbers (tiller/plant) counted at various times for the non-flooded and flooded rice.**



Columns headed by the same letter do not differ significantly at the 5% level by DMRT.

influenced by the imposition of the water regimes or application of the different S^0 fertilizer sources (data not presented).

The number of filled and unfilled grains were significantly influenced by water regime (Figure 2). The filled grain numbers in the flooded treatment (F) were significantly higher than that of the non-flooded treatment (NF) with the means of 578 grains/pot and 372 grains/pot, respectively (Table 3 and Figure 2).

Yield Parameters

(i) Straw and filled grain dry weights

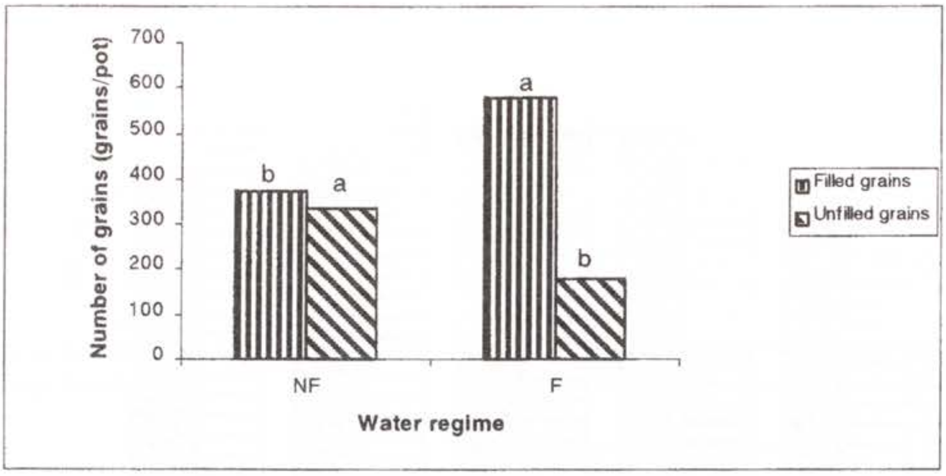
There was no significant water regime x S^0 fertilizer source interaction (Appendix 2) on straw dry weight (DW). However, application of the different S^0 coated fertilizer sources resulted in significant differences in mean straw DW (Table 4). A higher mean straw DW was recorded in the TSP+S^0f treatment with a

***Table 3.* Effects of the application of the different S^0 coated fertilizer sources on the number of filled grains of rice under flooded and non-flooded conditions.**

Filled grain numbers (grains/pot)			
S^0 fertilizer source	Flooded	Non-Flooded	Mean
Control	387	203	295 c
GP10	443	254	348 c
UNE511	645	297	471 b
UNE1	623	442	532 ab
TSP+S^0f	669	421	545 ab
TSP+S^0m	645	478	561 a
TSP+S^0c	636	514	575 a
Mean	578 a	372 b	

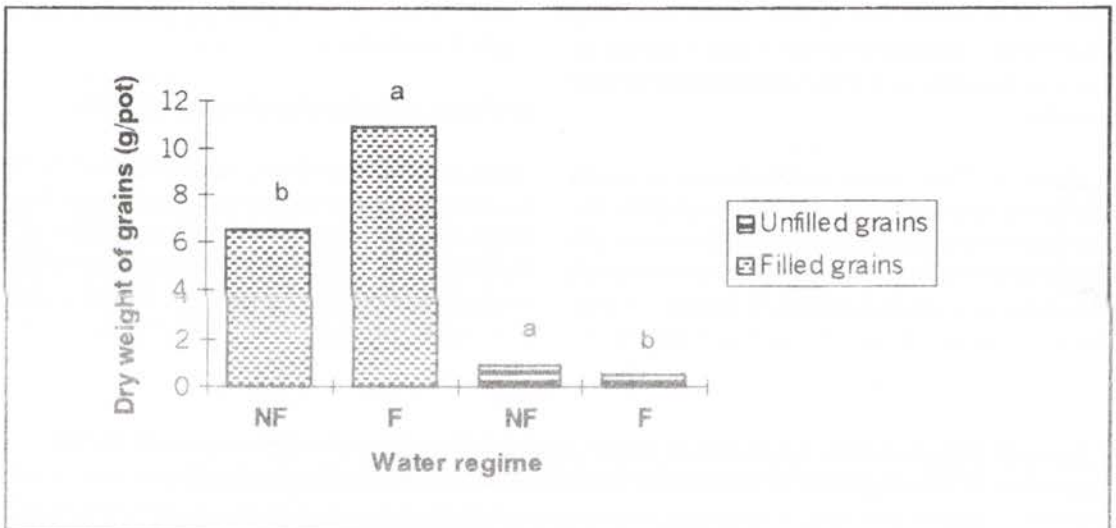
Mean values followed by the same letters in a column or row, are not significantly different at the 5% level by DMRT.

Figure 2. **Effects of water regimes on the number of filled and unfilled grains of rice.**



Columns headed by different letters within the two respective grain categories (filled and unfilled) differ significantly at the 5% level by DMRT.

Figure 3. **Effects of water regime on the dry weight of filled and unfilled grains of rice.**



Columns headed by different letters within the two respective grain categories (filled and unfilled) differ significantly at the 5% level by DMRT.

mean DW of 13 g/pot which was similar to that of UNE1, TSP+S°m, TSP+S°c and UNE511. Application of GP10 resulted in a lower mean straw DW (11.8 g/pot), but this did not differ significantly from that of UNE511, UNE1, TSP+S°m and TSP+S°c. The lowest straw DW was observed in the Control treatment with a mean of 7.2 g/pot.

The mean dry weights of filled grains were significantly influenced as a result of the applications of the different S° coated fertilizer sources (Table 4). Higher but similar mean dry weights of filled grains were observed in the coated fertilizers TSP+S°m, TSP+S°c, TSP+S°f and UNE1 with the means of 10.4, 10.3, 10.1 and 9.9 g/pot, respectively (Table 4). GP10 had the lowest mean DW of filled grains. There was no significant difference observed between the GP10 and the Control treatment.

The imposition of the two water regimes resulted in significant differences in mean DW of filled and unfilled grains (Figure 3 and Table 4). Flooding of the soils resulted in significantly increased DW of filled grains from a mean DW of 6.5 g/pot without flooding to a mean of 10.9 g/pot with flooding. In the case of unfilled grains, there were significantly lower unfilled grain mean dry weights in the flooded treatment (Figure 3 and Table 4).

Table 4. **Dry weight of rice straw and grain, and total dry weight of tops as influenced by the application of the different S fertilizer sources under flooded and non-flooded conditions.**

S material	Straw DW (g/pot)			Filled grain DW (g/pot			Total DW (g/pot)		
	F	NF	Mean	F	NF	Mean	F	NF	Mean
Control	6.9	7.4	7.2c	7.1	3.3	5.2c	14.0	10.7	12.4d
GP10	11.7	11.8	11.8b	8.3	4.4	6.4c	20.0	16.2	18.1c
UNE511	12.6	12.3	12.5ab	12.1	5.3	8.7b	24.7	17.6	21.2b
UNE1	13.4	12.2	12.8ab	11.7	8.0	9.9ab	25.1	20.2	22.7a
TSP+S°f	13.3	12.7	13.0a	12.7	7.5	10.1ab	26.0	20.2	23.1a
TSP+S°m	12.8	11.7	12.3ab	12.2	8.6	10.4a	25.0	20.3	22.7a
TSP+S°c	13.2	12.0	12.6ab	12.0	8.7	10.3a	25.2	20.7	22.9a
Mean	11.9 a	11.4 a		10.9 a	6.5 b		22.9 a	18.0 b	

Mean values followed by the same letter in a column or row within each rice component are not significantly different at the 5% level by DMRT.

((ii) Total dry weight of tops (straw + grain)

Table 4 indicates that the lowest mean total DW of tops was recorded in the Control treatment followed by GP10, which recorded a significantly lower mean total DW of tops compared to the UNE511 S° fertilizer source. UNE1, TSP+S°f, TSP+S°m and TSP+S°c recorded higher but similar mean total DW of tops. Flooding of soils significantly increased the mean total DW of tops from a mean of 18.0 g/pot without flooding to a mean of 22.9 g/pot with flooding (Table 4).

Sulfur Content and the Recovery of Fertilizer S in Leaves at each Leaf Harvest

(i) S content of leaves

Water regimes had a significant effect on S content of leaves only at 27 DAT, where the mean S content averaged over fertilizers was 0.25 and 0.30 mg/pot in the flooded and non-flooded treatments respectively. Application of the different S° coated fertilizer sources did not have any significant effects on S content of leaves at 27 DAT (Table 5). The Control treatment recorded a significantly lower S content of leaves compared to the S° coated fertilizer sources. A similar trend was observed at 41 DAT, where the lowest S content of leaves was recorded in the Control treatment, which was significantly lower than that of GP10 and UNE511 S° fertilizer sources. Lower and similar S contents of leaves were observed in the Control and GP10 treatments at 55 DAT. At 69 DAT, higher but similar S contents of leaves were observed in the TSP+S°m and TSP+S°c S° coated fertilizer sources.

(ii) Fertilizer S recovery in the leaves

Table 6 shows that at 27 DAT, flooding of soils significantly increased the mean percentage recovery of the fertilizer S from a mean percentage S recovery of 18% without flooding to a mean of 41% with flooding. Application of TSP+ S°c fertilizer resulted in a significantly higher recovery of fertilizer S in the rice leaves at the first leaf harvest (27 DAT) with a mean of 40%, although this was similar to that of the UNE1 (35%), TSP+S°m (34%) and TSP+S°f (31%) S° coated fertilizer sources. The lowest fertilizer S recovery in the rice leaves was recorded in the UNE511 S° fertilizer source.

There was a significant interaction between water regime and S° fertilizer source on the percentage fertilizer S recovery in the rice leaves at 41 DAT. That is, in the presence of floodwater, most of the fertilizers significantly improved their performances as far as recovery of the fertilizer S is concerned. At 55 DAT, the S° fertilizer sources UNE1, TSP+S°f, TSP+S°m, TSP+S°c recorded high but similar mean percentage fertilizer S recoveries. Flooding of soils also significantly increased the mean fertilizer S recovery. At 69 DAT, a similar trend was observed. Application of GP10 and UNE511 resulted in

Table 5. **Effect of S^0 coated fertilizer sources on S content (mg/pot) of rice leaves at different leaf harvest times.**

	S^0 Coated fertilizer materials						
Leaf harvest time	Control	GP10	UNE511	UNE1	TSP+S^0f	TSP+S^0m	TSP+S^0c
				S content			
27 DAT	0.22 b	0.30 a	0.27 a	0.28 a	0.30 a	0.30 a	0.30 a
41 DAT	0.15 d	0.22 c	0.24 bc	0.29 a	0.29 a	0.27 ab	0.28 ab
55 DAT	0.18 c	0.21 c	0.30 b	0.37 a	0.31 ab	0.32 ab	0.33 ab
69 DAT	0.15 c	0.18 de	0.22 cd	0.25 bc	0.26 bc	0.29 ab	0.31 a

Values followed by the same letter in a row within each harvest time do not differ significantly at the 5% level by DMRT.

Table 6. **Percentage fertilizer S recovery (%) in rice leaves from the different S^0 coated fertilizer sources measured at each harvest under flooded (F) and non-flooded (NF) conditions.**

	S^0 coated fertilizer materials						
Water regime	GP10	UNE511	UNE1	TSP+S^0f	TSP+S^0m	TSP+S^0c	**Mean**
			27DAT				
F	41	27	36	50	39	52	**41 a**
NF	0	5	34	11	28	27	**18 b**
Mean	**21 bc**	**16 c**	**35 ab**	**31 abc**	**34 ab**	**40 a**	
			41DAT				
F	34 abc	38 ab	50 a	43 ab	19 bcd	52 a	
NF	9 cd	0 d	29 abc	37 ab	29 abc	18 bcd	
			55DAT				
F	25	30	56	51	46	52	**43 a**
NF	0	7	32	26	19	28	**19 b**
Mean	**13 b**	**19 b**	**44 a**	**39 a**	**33 a**	**40 a**	
			69DAT				
F	13	28	60	57	45	47	**47 a**
NF	1	3	36	31	31	41	**24 b**
Mean	**7 b**	**16 b**	**48 a**	**44 a**	**38 a**	**44 a**	

Values followed by the same letter in a column or row within each harvest time are not significantly different at the 5% level by DMRT.

significantly lower mean percentage fertilizer S recovery at 69 DAT.

Sulfur Content and Recovery of Fertilizer S in the Straw and Grain Components

(i) S content of straw and grain

Flooding of the soils resulted in significant increases in the mean S content of straw and grain with the means of 7.5 mg/pot with flooding and 6.4 mg/pot without flooding for the straws, and 9.8 mg/pot with flooding and 5.7 mg/pot without flooding for the grains (Table 7). Application of the different S^0 coated fertilizer materials resulted in significant differences in the mean S content of straw and grain, and the mean total S content (Table 7).

Higher but similar mean S contents of straw were recorded in the S^0 coated fertilizers UNE1, TSP+S^0f and TSP+S^0c, followed by TSP+S^0m and UNE511, which were significantly lower. The lowest mean S content of straw was observed in the Control treatment, which was significantly lower than that of the GP10 S^0 coated fertilizer source (Table 7).

A similar trend was observed for the S contents of grain where higher but similar mean S contents were recorded in the UNE1, TSP+S^0f, TSP+S^0m and TSP+S^0c S^0 coated fertilizers. The Control and GP10 treatments recorded the lowest mean S contents of grain (Table 7).

(ii) Total S content of the tops (straw + grain)

When the S content of straw and grain was summed, a higher mean total S content in the rice tops was obtained in the UNE1 fertilizer treatment, but, this did not differ significantly from those of TSP+S^0f and TSP+S^0c S^0 coated fertilizer sources (Table 7). UNE511 recorded a significantly lower mean total S content in the rice tops, although this was significantly higher than that of the GP10 fertilizer treatment. The lowest mean total S content in the rice tops was observed in the Control treatment. Flooding of soils significantly increased the total S content in the rice tops from a mean of 12.1 mg/pot without flooding to a mean of 17.3 mg/pot with flooding (Table 7).

(iii) Fertilizer S recovery in the straw and grain

There was no significant water regime x S^0 coated fertilizer source interaction on the recovery of fertilizer S in the straw and grain components. Higher fertilizer S recovery was recorded in the UNE1 treatment with a mean percentage S recovery of 38.6% (Table 8), although this was not significantly different from those of TSP+S^0f and TSP+S^0c S^0 coated fertilizer sources.

The mean percentage fertilizer S recoveries in the straw were significantly lower in the UNE511 (13.7%) and GP10 (5.6%) S^0 coated fertilizer materials, which were similar.

The mean percentage recovery of fertilizer S in the grain (Table 8) shows a similar trend as has occurred

Table 7. **S contents of straw and grain, and the total S content as influenced by the application of the different S fertilizer sources under flooded and non-flooded conditions.**

S material	S content of straw (mg/pot)			S content of grain (mg/pot)			Total S content (mg/pot)		
	F	NF	Mean	F	NF	Mean	F	NF	Mean
Control	3.0	3.4	3.2d	5.0	2.5	3.7c	8.0	5.9	6.9e
GP10	6.0	5.6	5.8c	5.7	3.3	4.5c	11.8	8.9	10.4d
UNE511	7.2	6.6	6.9b	10.5	3.7	7.1b	17.7	10.3	14.0c
UNE1	10.3	7.9	9.1a	12.1	8.2	10.2a	22.4	16.1	19.3a
TSP+S^0f	9.2	7.4	8.3a	12.3	6.7	9.5a	21.5	14.1	17.8a
TSP+S^0m	7.4	6.6	7.0b	10.6	7.4	9.0a	18.0	14.0	16.0b
TSP+S^0c	9.7	7.4	8.6a	12.0	7.8	9.9a	21.7	15.2	18.5a
Mean	7.5 a	6.4 b		9.8 a	5.7 b		17.3 a	12.1 b	

Values followed by the same letter in column or row within each rice component do not differ significantly at the 5% level by DMRT.

in the straw, where application of UNE511 had a lower grain S recovery compared to the other S° coated fertilizer materials followed by GP10 which recorded the lowest (4%) S recovery in the grain (Table 8).

(iv) Total fertilizer S recovery in the rice tops

Higher but similar mean total fertilizer S recoveries were obtained in the treatments TSP+S°c, UNE1 and TSP+S°f with the means of 82.7%, 82.1% and 68.4%, respectively (Table 8). The lowest mean total recovery of fertilizer S in the rice tops was observed in the GP10 fertilizer treatment with a mean of 9.6%, which was significantly lower than that of the UNE511 (38.8%) treatment. Flooding of the soils significantly increased the mean total recovery of fertilizer S from 38.7% without flooding to 75.4% with flooding.

DISCUSSION

Number of Tillers and Grains

Applications of the different S° fertilizer sources under flooding appear to have contributed to the rapid increase in tiller numbers, thus, higher grain number (Table 2 and Figure 1). Visual observations during the course of the study, showed stunted growth and less tiller numbers in the Control treatment particularly in the early growth stages (Table 2), which are symptoms of S deficiency (Yosida and Chaudhry, 1979; Blair *et al*., 1979b). This is clearly shown in Table 3, where applications of the different S° fertilizer sources under flooding resulted in higher grain numbers than when they were applied to non-flooded conditions.

The number of tillers is approximately constant for any one variety under comparable conditions, however, tillering can be influenced by cultural conditions, plant spacings, amount of fertilizer applied, weeds and water availability (Grist, 1986). According to Grist (1986), if tiller numbers are few in number and produced within a short period of time, the ripening period of all is about equal. However, if tillers are numerous or produced over a lengthy period of time, a variable number of unproductive tillers can occur. Hence, a large number of tillers is not necessarily conducive to higher grain yield, because it is possible that unequal ripening may result.

In the current study, tiller numbers in the flooded condition, increased rapidly from 3.1 tillers/plant at 20 DAT to almost 4.0 tillers/plant at 27 DAT (Figure 1). Under non-flooding, tiller numbers increased slowly from 2.7 tillers/plant at 20 DAT to 4.6 tillers/plant at 55 DAT (Figure 1). De Datta *et al*. (1970), indicated that tiller number increases as the depth of water decreases and as the soil dries, but, when the soil drying reaches a relatively extreme level, the tiller number reduces sharply. In the present study, under flooding, water was maintained at a depth of about 4 cm at all times whereas under non-flooding, water was maintained at or near field capacity. The consistently lower tiller number under flooding after 27 DAT, may thus be due to the above phenomenon. However, despite the lower tiller numbers under the flooded conditions, the filled grain

Table 8. **Effect of application of the different S fertilizer sources on recovery of fertilizer S in rice straw and grain, and total recovery of fertilizer S in the tops under flooded and non-flooded conditions.**

S material	Percentage S recovery (%)								
	Straw			Grain			Total		
	F	NF	Mean	F	NF	Mean	F	NF	Mean
GP10	11.1	0	5.6c	8	0	4.0d	19.1	0	9.6d
UNE511	27.4	0	13.7c	37.8	12.3	25.1c	65.2	12.3	38.8c
UNE1	46.3	30.9	38.6a	50.4	36.5	43.5ab	96.7	67.4	82.1a
TSP+S°f	44.7	18.8	31.7ab	46.4	26.9	36.7abc	91.1	45.7	68.4ab
TSP+S°m	33.6	23.7	28.7b	39.9	24.6	32.3bc	73.5	48.3	60.9b
TSP+S°c	44.5	26.0	35.2ab	62.2	32.7	47.5a	106.7	58.7	82.7a
Mean	34.6 a	16.7 b		40.8 a	22.2 b		75.4 a	38.7 b	

Values followed by the same letter in column or row within each rice component do not differ significantly at the 5% level by DMRT.

number was significantly higher than under non-flooding (Table 3 and Figure 2). This implies that the rapid increase in tiller numbers and the early attainment of maximum tillering under flooding, had a positive influence on grain production. Furthermore, the higher number of unfilled grains under non-flooding (Figure 2) appears to be the direct result of the slow increase and late attainment of maximum tillering. This seems to be in conformity with Grist (1986), where he indicated that tillers produced over a longer period of time may result in the production of a variable number of unproductive tillers or unequal grain ripening.

Straw and Grain Yields

In relation to straw yield, it is apparent that applications of the different S° fertilizer sources increased the DW of straws, however, there were non-significant differences in straw DW amongst the different S° fertilizer sources (Table 4). However, grain yield was significantly influenced by the application of the different S° fertilizer sources. Application of GP10 and UNE511 fertilizer treatments resulted in lower grain yields (Table 4). The data on the total dry weight of tops (Table 4) show that the applications of GP10 and UNE511 resulted in significantly lower total dry weight of tops. Flooding of the soils resulted in higher total DW of tops (22.9 g/pot) compared to the non-flooded treatment, which recorded 18.0 g/pot. The Control treatment recorded the lowest total dry weight of tops under both water regimes. Similar results were also found by Dana *et al.* (1994a) and Blair *et al.* (1994), who found that the application of GP10 (HF) resulted in significantly lower relative whole plant and grain yields.

Sulfur is required early in the growth of rice plants and if it is limiting during early growth, the final yield will be reduced (Blair *et al.* 1979b). Dana *et al.* (1994a) and Blair *et al.* (1994) found that the application of UNE1 gave consistently higher yields irrespective of the water regimes (non-flooded and flooded) employed. In the current study, non-significant differences in straw and grain yields amongst the S° fertilizer sources TSP+S°f (fine), TSP+S°m (medium) and TSP+S°c (coarse) were obtained. This means that the different S° particle sizes bound onto the surfaces of TSP granules had a similar effect on the straw and grain yields. Dana *et al.* (1994a), attributed the different responses principally to the different techniques employed in the production of the products, resulting in different coat strengths. According to Dana *et al.* (1994a), UNE1 was produced using a rotating drum-seed coating device by binding S° (particle size <0.1 mm or <100 µm) onto the surface of 2-4 mm diameter TSP granules with polyvinyl alcohol as a binder. In the present study, TSP+S°f, TSP+S°m and TSP+S°c were prepared in the similar manner as UNE1, but different S° particle sizes were used (fine = 53-154 µm; medium = 154-263 µm and coarse = 263-328 µm). Calcium lignosulfonate was used to bind S° particles onto the surfaces of TSP granules of 2-2.8 mm diameter. The information booklet (No.8) on Gold-phos by Hi-Fert Pty Ltd (1997) indicated that the Gold-phos product (GP10) is made by milling S° to an agronomically available size (<250 µm) and chemically bonding it onto TSP granules. The lower yields obtained in both the UNE511 and GP10 products seem to be related primarily to the way these products were prepared and not necessarily due to the different S° particle sizes or coating materials used. It is possible therefore, to suggest that these products (UNE511 and GP10) were prepared in such a way that impairment of water penetration into the granules was increased thereby, inhibiting the dispersion of S° in the soil.

The imposition of the two water regimes also influenced straw and grain yields. Grain yield under non-flooded condition was significantly lower with a mean of 6.5 g/pot than that under flooded condition with a mean grain weight of 10.9 g/pot (Figure 3). Similar results were also reported by Dana *et al.* (1994a) and Ismunadji (1985), who found higher grain yields under flooded conditions than under non-flooded conditions. However, these authors found higher straw yields under non-flooded than under flooded conditions whereas in the current study, a non-significant difference in straw yield between non-flooded and flooded conditions was observed. Visual observations during the course of the experiment, showed that under the non-flooded condition, the rice plants were generally shorter but had more tillers particularly at the later growth stages (Figure 1). On the other hand, under the flooded condition, the plants were generally taller but had less number of tillers (Figure 1). The non-significant difference in straw yield under these two water regimes may be due to the compensatory effect of higher tiller numbers under non-flooded and taller plants under flooded conditions. That is, it is possible for the generally shorter plants under the non-flooded condition to have lower straw yield if it were not for the higher tiller numbers. Similarly, it is possible to suggest that although the plants under the flooded condition had less number of tillers, which may contribute to lower straw yield, the fact that they were generally taller may have compensated for any decrease in straw yield that may have eventuated if the plants were shorter as under the non-flooded condition.

Sulfur Content and Recovery of Fertilizer S in the Leaves, Straw and Grain

Sulfur content of leaves in the Control and GP10 treatments tend to decline with each leaf harvest (Table 5) whereas with the other S° fertilizer sources the S contents of leaves were generally higher and constant at each leaf harvest. Similarly, the data on percentage fertilizer S recovery (Table 6) indicate that the percentage fertilizer S recovered in the leaves from the GP10 and UNE511 treatments were significantly lower at each leaf harvest compared to the other S° fertilizer sources.

The fact that the higher S content of leaves were observed in the GP10 and UNE511 treatments at the early growth stages (27 DAT), is because the rice plants in the early growth stages were relatively smaller, thus the amounts of S released from the GP10 and UNE511 fertilizer sources were sufficient to be recovered in the leaves at the higher amounts even though they were releasing little S. However, as the rice plants mature the S released from these two fertilizer sources was distributed to other leaves or plant parts and because the fertilizers were releasing little S, less amount of fertilizer S was recovered in the leaves, hence, the generally lower S contents in the leaves at the later growth stages (Table 5). On the other hand, the other S° fertilizer sources were able to release higher amounts of S at a sustained level, therefore the S contents in the leaves (Table 5) and the percentage fertilizer S recovered in the leaves from the respective S sources (UNE1, TSP+S°f, TSP+S°m and TSP+S°c) were generally high at each leaf harvest (Table 6).

The data on S contents of straw and grain, and the total S content (Table 7) indicate that the GP10 and UNE511 treatments recorded lower straw and grain S contents. This may be attributed to lack of S as a result of little S being released by these particular fertilizer materials. Table 8 shows that the mean percentage recovery of fertilizer S in the straw and grain, and the mean total S recovered in the rice tops (total) were significantly lower in the GP10 and UNE511 fertilizer materials. These results further support the assertion that both GP10 and UNE511 released little S in comparison to the other S fertilizer sources and it is in agreement with the results of Dana *et al.* (1994b), who found that the release of S from UNE1 (polyvinyl alcohol) and UNE3 (calcium lignosulfonate) products were similar and greater than the release from HF (GP10) product. Blair *et al.* (1994), found a higher amount of fertilizer S recovered in the organic S pool from HF (GP10), and they attributed this to the slower release of S from HF, which resulted in the poor growth of pastures. They also found that the immobilization of S, which was released from this product was the main reason for the higher S transformation into the organic S fraction.

Flooding of the soils significantly increased the total S content in the rice tops from a mean of 12.1 mg/pot without flooding to a mean of 17.3 mg/pot with flooding, and the mean total recovery of fertilizer S from 38.7% without flooding to 75.4% with flooding (Table 8). This means that oxidation of S° was greater under the flooded condition. However, this is in contrast to studies, which demonstrated the S° oxidation is favored at field moisture capacity (Janzen and Bettany 1987c; Nevell and Wainright 1987). However, Dana *et al.* (1994a), found that oxidation of S° was rapid under both flooded and non-flooded conditions. Within a flooded soil, there are aerobic and anaerobic zones, therefore, oxidation and reduction reactions can occur at the same time in the different parts of the flooded soil (Blair and Lefroy 1987). Rice plants generally occupy a large volume of the planted soil so that oxidized zones occur which allow for the growth and metabolism of aerobic microorganisms (Freney *et al.* 1982). As part of the experiment, these S° coated products were placed under water in petri- dishes for a period of 5 days. It was observed that UNE1, TSP+S°f, TSP+S°m and TSP+S°c disintegrated and dispersed faster after a day (data not presented), which would mean that oxidation of S° by the S oxidizing microorganisms took place quickly.

Many factors influence the oxidation of S° and these include soil temperature (Parker and Prisk 1953; Nor and Tabatabai 1977; Janzen and Bettany 1987b; Germida and Janzen 1993), soil moisture and aeration (Burns 1968; Janzen and Bettany 1987c; Germida and Janzen 1993), soil pH (Nor and Tabatabi 1977; McCready and Krouse 1982); nutrient availability (Burns 1968; Lawrence and Germida 1988), sulfur oxidizing microorganisms (Vitolins and Swaby 1969; Konopka *et al.* 1986) and particle size of the S° (Li and Caldwell 1966; Weir 1975; Koehler and Roberts 1983; Janzen and Bettany 1986; Germida and Janzen 1993).

In the present study, the different S° particle sizes used did not have any significant influences on the dry weight of straw and grain irrespective of the 2 water regimes imposed. Koehler and Roberts (1983), observed that S° particle size of 250-350 µm provided some increase in lucerne yield when applied at higher rates, but when applied at lower rates very little effect on lucerne yield was obtained. Santoso *et al.* (1995), found no significant difference in S° (150-250 µm) oxidation when S° was applied at 10 mg/g soil. In a similar study, Lefroy *et al.* (1997), found higher S° oxidation when S° was applied at 35.2 mg/g soil (» 20 kg S/ha). In the current study, the rate of S° applied at 10 kg/ha with the coarse particle size (263-328 µm) would have had a lower specific surface area and amount of S, resulting in lower oxidation (Lefroy *et al.* 1997) thus, contributing to the non-significant effects of the different S° particle sizes on the total dry weights of rice tops and the S content and recovery of fertilizer S in the straw and grain.

As indicated earlier, the different S responses obtained in the current study seem to be due largely to the way the individual product was prepared. For example, in the case of UNE511, although the coating material used was the same as that in UNE1, because it was prepared differently, the results obtained differ significantly to that of UNE1. Hence, it may be suggested that selection of the right coating material should be accompanied by the precise following of the right procedures in the preparation of each individual product to realize the full potential of a coated fertilizer product.

Comparison of the different Elemental S Coated Fertilizer Sources

In general, the results in the current study clearly demonstrated that amongst the S^0 coated fertilizer sources, UNE1 and the TSP+S^0 products with the fine, medium and coarse S^0 particle sizes were more effective than the other sources. This was due principally to the use of water-soluble adhesives (polyvinyl alcohol and calcium lignosulfonate) to bind S^0 to the TSP granules. However, it has also been observed that the way each individual product was prepared contributed partly to its effectiveness. This is clearly shown in the case of UNE511, that although it has the same coating material as UNE1, because it was subjected to excessive warm air during its preparation, the coat was extra hardened which tended to impede water penetration into the granules and the consequent dispersion of S^0 into the soil. The application of GP10 also generally resulted in poorer S response than UNE1 and the TSP+S^0 products. It has been highlighted previously that this particular product was prepared by milling S^0 to <250 µm and chemically bonding it on the TSP granules. It is most probable that during this process the coat strength could have been consolidated, which, resulted in the impairment of water penetration into the granules thus preventing the dispersion of S^0 into the soil. It seems obvious, therefore, that the choice of a suitable coating material should be accompanied by the proper preparation techniques of the product, so that not only it can release its nutrient content but also release them when they are required by plants at the optimum.

The rate of nutrient release from slow release fertilizers was described by a number of researchers as being controlled by the slow diffusion of the nutrient ions through the membrane to the soil (Lunt and Oertli, 1962; Ahmed *et al.* 1963). Kochba *et al.* (1990), proposed that the mechanism responsible for nutrient release is the diffusion of water vapor into the granule through the hydrophobic membrane (coat material) and the subsequent bursting or expansion of the membrane, which lead to an accelerated outward flow of the saturated solution from the coated granules. In addition, they proposed that timing of the nutrient release of the individual granules was a random phenomenon, similar to radioactive decay. This proposition assumes that the release process follows first order kinetics. That is, the granule population is considered to be uniform and that the likelihood of the bursting of any given granule is the same throughout the release process. However, Kochba *et al.* (1994) reported that studies on slow release rate and individual granules and population behavior showed that individual granules within a given population of a slow-release fertilizer have a different release pattern. They found that some granules released their nutrient content within a few days, whilst others released their nutrient contents in a period of 100 days. Furthermore, the authors observed that the release process contains a delay mechanism that has a different duration for different individual granules and that a "starter" fraction reacts soon after the exposure to water while others react later. Studies on N release from polyolefin-coated urea (POCU) (Takahashi and Ono 1996), indicated that individual granules of POCU had different weights and N release rates. Also, they found that an increase in individual weights of POCU resulted in a decrease in the N release and they attributed this relationship to the coating thickness.

From the above discussions on nutrient release as described by the various authors, it is apparent that for a coated fertilizer to be more effective, the coating material must allow water to diffuse through it into the granules and because individual granules within a population have a different release pattern (Kochba *et al.* 1994), maximum penetration of water through the coat into most granules should be facilitated, so that each individual granule may release its nutrient content according to its release pattern or behavior. It is pertinent, therefore, that in the process of coating fertilizer granules, the water-soluble nature or characteristics of the coating material should be maintained so that water penetration into the granules, which is the beginning of the entire process of fertilizer nutrient release, cannot be impeded.

CONCLUSION

On the basis of the results discussed above, it is clear that UNE1, TSP+S^0f (fine), TSP+S^0m (medium) and TSP+S^0c (coarse) are effective S fertilizer sources for rice under non-flooded and flooded conditions compared to GP10 and UNE511 S^0 fertilizer sources. It is also evident that the use of water-soluble adhesives such as polyvinyl alcohol and calcium lignosulfonate to bind S^0 particles on to TSP products contributed significantly to the effectiveness of these products. Moreover, the results indicated that the way a product is prepared has a strong influence on its effectiveness. The use of the different S^0 particle sizes of 53-154µm, 154-

263μm and 263-328μm did not result in any significant differences, and these could be considered as agronomically suitable in respect of providing S nutrition to rice plants under non-flooded and flooded conditions.

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Appendix 1. **Anova for filled grain numbers**

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB
GRAND MEAN	1	9499064.00000	9499064.00000	2212.1680	0.00000***
R	2	0024776.38000	0012388.19000	0002.8850	0.07386-
W	1	0443520.80000	0443520.80000	0103.2883	0.00000***
F	6	0445365.30000	0074227.55000	0017.2863	0.00000***
WF	6	0047750.09000	0007958.34900	0001.8534	0.12756
RWF/	26	0111644.20000	0004294.00700		

Appendix 2. **Anova for the straw (tops) dry weights**

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB
GRAND MEAN	1	5765.30400000	5765.30400000	7267.3840	0.00000***
R	2	0001.58370500	0000.79185270	0000.9982	0.38224
W	1	0003.12537200	0003.12537200	0003.9396	0.05781-
F	6	0149.62500000	0024.93750000	0031.4347	0.00000***
WF	6	0004.14248500	0000.69041420	0000.8703	0.52796
RWF/	26	0020.62612000	0000.79331210		

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