CHAPTER 3

SULFUR COATED FERTILISER MATERIALS AND THEIR EFFECTIVENESS AS SULFUR SOURCES FOR RICE UNDER FLOODED AND NON-FLOODED CONDITIONS

3.1 INTRODUCTION

Rice (*Oryza sativa L.*) is the most important food crop in the world, particularly in the Asian and Indian subcontinent. According to IRRI's 1994 program report (IRRI, 1995), of the total 81 million hectares of irrigated rice, Asia alone has 75 million hectares and produces more than 70% of the world's rice. The report also indicated that Asia has almost 40 million hectares planted to rainfed lowland rice which is mostly in the South and Southeast Asia region. Rice grown in the upland ecosystem makes up 19% of the total rice production.

The influence of P on S^c oxidation was covered in Chapter 2 where various authors reported increased S^c oxidation rates, increased plant growth, increased fertiliser-S uptake and higher percentage of plant S derived from fertiliser in the presence of P (Janzen and Bettany, 1987b; Lawrence and Germida, 1988; Dana, 1992; Chinoim, 1994; Sholeh, 1995; Santoso *et al.*, 1995). In rice, Dana (1992) attributed the differences between the TSP-S products he studied to the method of bonding of the S coat to the TSP granules. Investigating the effects of different manufacturing techniques on availability of SO_4^{2-} from mixtures of S^c with TSP, Boswell *et al.* (1996) attributed the differences resulting from the different methods of preparing S^c mixtures to the particle size of the S^c released when granules dispersed. The authors also showed that irrespective of whether the sintering or blending method was used, mixtures that contained sulfur particles of diameter <75 μm were more effective. It appears that whilst coating of S^c onto finished fertiliser products such as TSP is a beneficial process, the important factors that tend to contribute to the effectiveness of such a product are the right particle size of the S^c and the preparation method used in the coating process of such a product. However, it is desirable to use S coated fertilisers that are easy to handle and at the same time possess the nutrient release patterns synchronized to the demand of the crop.

This study was aimed at investigating the effectiveness of a range of S coated TSP fertiliser materials in rice under flooded and non-flooded conditions.

3.2 MATERIALS AND METHODS

3.2.1 Experimental Design

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, NSW, Australia. The experiment consisted of a factorial combination of 6 sources of fertiliser S materials [Goldphos10 (GP10), UNE511, UNE1, TSP+S°f (fine), TSP+S°m (medium) and TSP+S°c (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). Description of the coated TSP fertiliser UNE1 is given by Dana (1992) and Dana *et al.* (1994a). UNE511 was made in the similar manner as UNE1 but during the drying process, its coat was hardened by blowing an excessive amount of warm air from a hair dryer. GP10 is a commercial S coated TSP (Goldphos10) which contains 18% P and 10% S. It is manufactured by Hi-Fert Pty Ltd, Australia.

3.2.2 Soil Sampling and Preparation

The surface layer (0-15 cm) of the soil was collected from a natural pasture site about 100 m from the New England Highway at Uralla, NSW. The soil was then air-dried and processed through a soil shredder to achieve a good mix. This also facilitated the removal of extraneous materials such as stones and plant debris with ease. Prior to weighing and bagging, the soils were passed through a 2 mm sieve to obtain a uniform soil particle size. This particular soil was used in previous experiments and it is reported to be a sulfur-deficient Aquic Haplustalf (Anderson, 1988; Chaitep, 1990; Dana, 1992). The chemical characteristics of the soil used in the experiment are presented in Table 3.1.

3.2.3 S Coated Fertiliser Preparations

To obtain the different particle sizes of 53-154 μm (fine), 154-263 μm (medium) and 263-328 μm (coarse), S° was sieved through the required sieve sizes by the wet-sieving method. In this method, the S° material (100% S) was washed lightly with the running tap water through the above sieve sized screens. The process began by washing the S° material through the coarser sized sieve (328 μm) and those particles that did not pass through this particular sieve were discarded, and particles that passed through were further washed using the second sieve (263 μm). Particles that did not pass through this particular sieve were retained (particle size between 263-328 μm), while those that passed through were washed again using the third sieve (154 μm) so that the particles which did not go through were retained as particle size between 154-263 μm. Finally, the particles that went through the 154 μm sieve were again washed through the last sieve (53 μm sized sieve). As above, the particles that did not pass through were retained as the particle size between 53-154 μm. The particles <53 μm were discarded. The three different particle size S° materials were then thoroughly air-dried and stored in plastic jars which were used to coat the triple superphosphate (TSP) granules.

Table 3.1 Chemical characteristics of the soil used in the study.

Soil characteristic	Value
Colwell P	17.0 μg/g soil
Organic P	135.8 μg/g soil
Total P	275.0 μg/g soil
Total S (KCl-40)	91.4 μg/g soil
pH (1.5: 0.01 M $CaCl_2$)	4.5
pH buffer capacity	0.01 mol/kg dry soil
Organic carbon	0.87 %
ECEC	32.0 mmol (p+)/kg
Exchangeable cations expressed as a % of ECEC	
Ca	69.9 %
Mg	10.2 %
K	4.9 %
Na	5.4 %
Al	9.5 %

(Sources: Anderson, 1988; Chaitep, 1990; Dana, 1992; Chinoim, 1994)

Before the TSP (20-23% P) granules were coated with S°, they were dry-sieved using 2 different sized sieves (2.0 and 2.8 mm diameter) and following the similar procedure as in wet-sieving, the TSP granules >2.8 mm were discarded and those that passed through were sieved through the 2.0 mm sized sieve. Granules <2.0 mm diameter were eliminated and granules between 2.0-2.8 mm diameter were retained and used in the experiment. Likewise, GP10 was sieved using the same sieve sizes and procedure as used for TSP.

3.2.4 Coating of TSP Granules with Elemental Sulfur

To coat the TSP granules with the S° material, 20 g each of the three different S° particle sizes were weighed. The 20 g S° material was then mixed 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° /calcium lignosulfonate mixture and mixed thoroughly with a glass rod. To obtain a good coated material, the mixture was transferred to a rotating drum and a slightly warm air current blown over the granules. The S coated materials, with the 3 different particle sizes, were then air-dried and stored in three different plastic jars.

3.2.5 Analysis of the S Coated TSP Granules

To measure the S content of the coated materials, the Combined Phosphorus and Sulfur Digest Method for Soils and Fertilisers by Till *et al.* (1984), was employed. The S and P rates used in the experiment (10 kg S/ha and 46 kg P/ha, respectively) were thus calculated based on the S and P contents of the coated materials, as obtained from the analysis, and the surface area of the pots.

3.2.6 ^{35}S Labelling of the Soil Samples

Prior to potting, 42 lots of 1.85 kg of soil were weighed and put in clear plastic bags. ^{35}S was then used to labelled 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 (0.893 MBq/pot). 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 labelled soil samples were then kept in the soil 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. The pots used in the experiment were 183 cm^2 in surface area. The pots were then transferred to the glasshouse, manually irrigated with deionized water to field capacity and were ready for basal nutrients which were applied a day later.

3.2.7 Basal Nutrients and Treatment Applications

Only nitrogen and potassium were applied as basal nutrients and these were mixed thoroughly with the soils. These were applied in solutions at the rates of 100 kg N/ha and 10 kg K/ha, and they 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 (var. IR30) seedlings which were grown in quartz sand were transplanted per pot. The treatments were not immediately imposed because it took about a week for the seedlings to adjust so that during this period those rice seedlings that failed to establish or died, were replaced. After a week, the six different S coated fertiliser materials and water regimes (flooded and non-flooded) were imposed. The S coated fertiliser 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 about 4 cm above the soil surface and maintained at that level until during 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. N was applied again 30 and 45 days after transplanting (DAT) at 40 kg/ha. Five weeks after the treatment applications, the rice plants showed K deficiency symptoms, therefore, a further 20 kg K/ha as KCl (70.4 mg KCl/pot) was added. The rice plants recovered dramatically after the K application. The application rates of P and S of the S coated fertiliser materials are presented in Table 3.2.

Table 3.2 Application rates (mg/pot) of P and S of the S coated fertiliser 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	18.00	10.00	183.00	32.94	51.24	222.49
UNE511	17.43	9.68	189.00	32.94	51.24	222.50
UNE1	20.00	10.00	183.00	36.60	47.58	206.60
TSP + S^o (53-154μm)	20.68	10.31	177.49	36.70	47.48	206.17
TSP + S^o (154-263μm)	20.33	11.29	162.09	32.95	51.23	222.45
TSP + S^o (263-328μm)	20.25	11.57	158.17	32.02	52.23	226.44

3.2.8 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 was 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 then 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 back 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.

3.2.9 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 leaving the empty panicles intact with the rest of the straw, and later sorted into filled and unfilled grains. The number of the filled and unfilled grains were also counted and recorded. These were then dried at the oven at 80° C for 48 hours and after cooling, their dry weights were recorded. The straw was harvested by cutting approximately 1 cm above the soil surface and 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.

3.2.10 Laboratory Analyses

Laboratory analyses of the leaf samples for each harvest was performed by adding 2 mL of 7:3 (v/v) mixture of perchloric acid ($HClO_4$) (70%) and hydrogen peroxide (H_2O_2) (30%) to each bottle and sealed tightly, following the procedures outlined by Anderson and Henderson (1986) for Sealed Chamber Digest for P, S, K, Na, Mg, Ca and trace element determination. After a predigestion period of 2 hours at room temperature, 1 mL of H_2O_2 was added, sealed and left in an oven at 80° C for 30 minutes. After cooling, a further 1 mL of H_2O_2 was added and allowed to digest for 1 hour. The digestion mixture was allowed to cool and then distilled water was added to make up to volume. The digests were then filtered using a Whatman No.1 filter paper.

Total S in the leaves for each sampling times (27 DAT, 41 DAT, 55 DAT and 69 DAT) was measured by the Inductively Coupled Plasma Optical Emission Spectrometer (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 fertiliser 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 fertilisers were estimated as (1-SRR) $\times$ 100%.

To analyze total N content in the straw and grain, a subsample for each treatment was weighed (1.0 g and 3.0 g for straw and grain respectively), and using a Near Infrared Spectrophotometer (NIRS), the N contents for the respective components were determined. For analysis of total S in the straw and grain, a subsample of 0.2 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 and the recovery of the fertiliser S by the rice plants was calculated using the reverse dilution technique (Shedley *et al.*, 1979). Testing of the granule strength of the different S fertiliser sources used in the experiment was conducted by Dr Terje Tande at Norsk Hydro Research Centre Porsgrunn, Norway.

3.2.11 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 a probability level of 5% or less are considered significant.

3.3 RESULTS

3.3.1 Yield Components

(i) Tiller numbers: There were significant differences in the number of tillers observed at different counting times (Figure 3.1). At 20 DAT, the number of tillers produced in the non-flooded treatment was significantly lower than that of the flooded treatment. The highest number of tillers produced in the flooded treatment was observed at 27 DAT, although this was not significantly different from that of the non-flooded treatment with the means of 3.8 and 4.0 tillers/plant for the non-flooded and flooded treatments, respectively. The highest number of tillers produced in the non-flooded treatment was observed at 55 DAT with the mean of 4.6 tillers/plant. At 69 DAT, the number of tillers under the flooded treatment declined dramatically as compared to the tiller numbers in the non-flooded treatment. Figure 3.1 also shows that tiller numbers in the flooded treatment were consistently lower after the second tiller count (27 DAT) compared to the non-flooded treatment.

The effects of the different S fertiliser sources on tiller numbers were significant at 20 and 27 DAT (Table 3.3). At 20 DAT, higher tiller numbers were observed in the TSP+S°f, TSP+S°m, TSP+S°c, UNE1 and UNE511 S fertiliser sources which were similar. At 27 DAT, application of UNE511 resulted in a significantly lower number of tillers which was similar to that of the Control treatment. No significant differences in tiller numbers were observed between the different S fertiliser sources at 55 and 69 DAT.

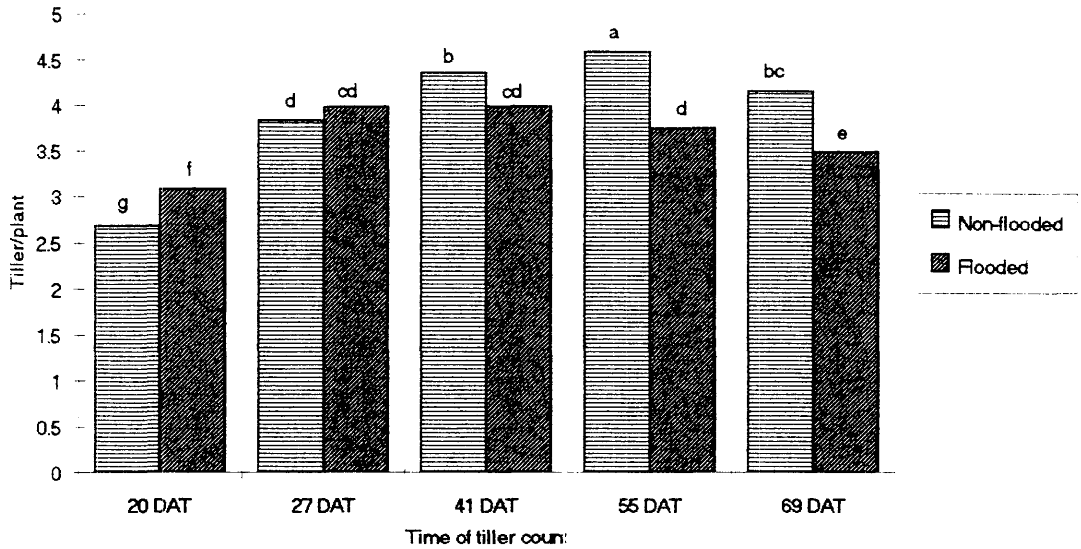

Figure 3.1 Number of tillers (tiller/plant) counted at various times for the non-flooded and flooded rice. Columns headed by the same letter do not differ significantly at the 5% level by DMRT.

Table 3.3 Number of tillers (tiller/plant) counted at various times as influenced by the different S fertiliser sources.

	S fertiliser sources						
Time of count	Control	GP10	UNE511	UNE1	TSP+ S°f	TSP+ S°m	TSP+ S°c
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.

(ii) Number of filled and unfilled grains: The mean number of filled and unfilled grains were significantly influenced by water regime (Figure 3.2). The filled grain numbers in the flooded (F) treatment were significantly higher than that of the non-flooded (NF) treatment with the means of 578 grains/pot and 372 grains/pot, respectively (Figure 3.2 and Table 3.4). With respect to the number of unfilled grains, the non-flooded treatment contributed significantly to the large number of unfilled rice grains compared to the flooded treatment (Figure 3.2).

There was no significant water regime x S fertiliser source interaction on the number of filled grains. However, the application of the different S fertiliser sources resulted in significant differences in the mean number of filled grains (Table 3.4). 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 fertiliser sources. No significant differences in mean filled grain numbers were recorded in the UNE1, TSP+S°f, TSP+S°m and TSP+S°c, and between UNE511, UNE1 and TSP+S°f S fertiliser sources (Table 3.4). Application of the different S fertiliser sources did not have any significant effects on the number of unfilled grains, and panicle numbers were neither influenced by the imposition of the water regimes or application of the different S fertiliser sources (data not presented).

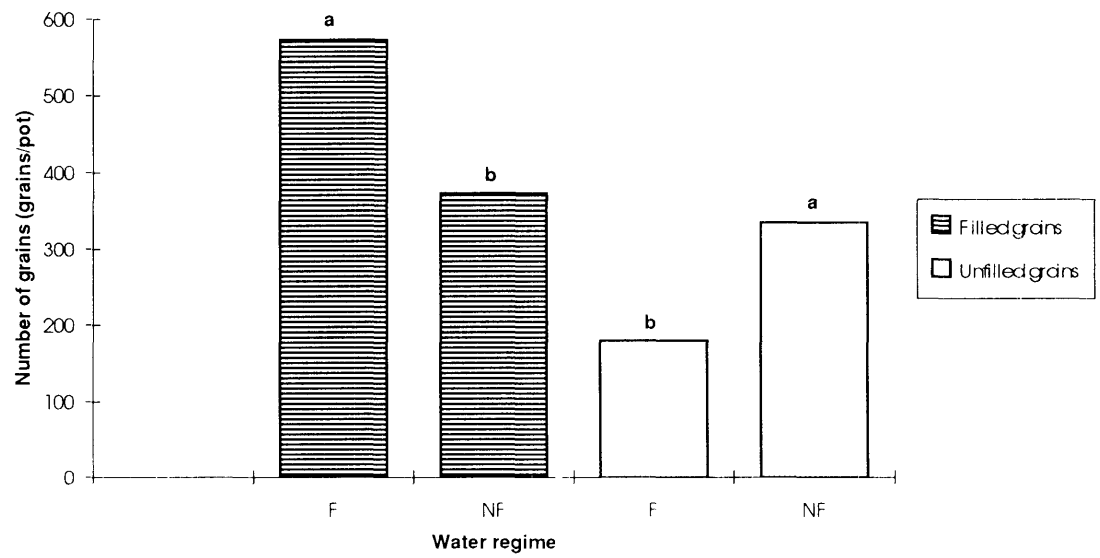

Figure 3.2 Effects of water regimes on the number of filled and unfilled rice grains / pot. Columns headed by different letters within the two respective grain categories (filled and unfilled) differ significantly at the 5% level by DMRT.

Table 3.4 Effects of the application of the different S fertiliser sources on the number of filled grains of rice under flooded and non-flooded conditions.

	Filled grain numbers (grain/pot)		
S fertiliser 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°f	669	421	545 ab
TSP+S°m	645	478	561 a
TSP+S°c	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.

3.3.2 Yield Parameters

(i) Dry weight (DW) of straw: There was no significant water regime x S fertiliser source interaction on straw DW. However, application of the different S fertiliser sources resulted in significant differences in mean straw DW (Table 3.5). A higher mean straw DW was recorded in the TSP+S°f treatment with a mean DW of 13.0 g/pot which was similar to that of UNE1, TSP+S°m, TSP+S°c and UNE511 treatments. 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 recorded in the Control with a mean of 7.2 g/pot. There were no significant differences in mean straw dry weights between the two water regimes (Table 3.5).

(ii) Dry weight of filled and unfilled grains: Application of the different S fertiliser sources did not influence the dry weights of unfilled grains (data not presented). The water regime x S fertiliser source interaction on filled grain yield was not significant. The mean dry weights of filled grains were significantly influenced as a result of the application of the different S fertiliser sources (Table 3.5). Higher mean dry weights of filled grains were recorded in the coated fertilisers 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 3.5). Nonetheless, the differences amongst these means were not significant. No significant differences in mean DW of filled grains were recorded between the

UNE511, UNE1 and TSP+S°f treatments. Applications of GP10 resulted in 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 (Table 3.5 and Figure 3.3). Flooding of the soils significantly increased the 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 3.3).

Table 3.5 Dry weight (g/pot) of rice straw and grain, and total dry weight of tops as influenced by the application of the different S fertiliser sources under flooded (F) and non-flooded (NF) conditions.

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

(iii) Total dry weight of tops (straw+grain): Table 3.5 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 fertiliser source. The S fertiliser sources UNE1, TSP+S°f, TSP+S°m anc TSP+S°c recorded higher but similar mean total DW of tops. Flooding of the soils significantly ircreased 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.

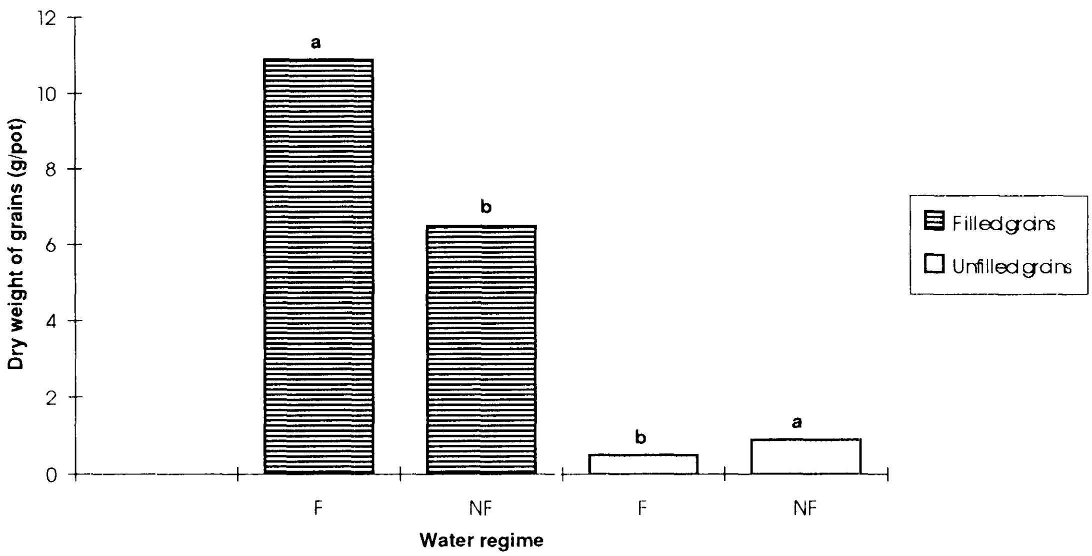

Figure 3.3 Effects of water regime on the dry weight of filled and unfilled rice grains / pot. Columns headed by different letters within the two respective grain categories (filled and unfilled) differ significantly at the 5% level by DMRT.

3.3.3 S Concentration, S Content and the Recovery of Fertiliser S in Leaves at each Leaf Harvest

(i) Sulfur concentration in leaves: Water regime had a significant effect on S concentration in the rice leaves only at 27 and 41 DAT. The mean S concentration averaged over fertilisers was 0.19 and 0.30% in the flooded and non-flooded treatments respectively at 27 DAT and 0.15 and 0.17% at 41 DAT. Application of the different S fertiliser sources resulted in significant differences in S concentration in the rice leaves (Table 3.6). At 27 DAT, a higher S concentration in the leaves was observed in the TSP+S°f S fertiliser source which was similar to that of TSP+S°m, TSP+S°c, UNE1 and GP10 S fertiliser sources. A similar trend was observed at 41, 55 and 69 DAT, however at these times GP10 had consistently lower S concentration in the leaves compared to most of the other S fertiliser sources. The Control treatment also had consistently lower S concentration in the rice leaves when observed at the different times.

Table 3.6 Effect of S fertiliser sources on S concentration (%) and S content (mg/pot) of rice leaves at different leaf harvest times.

	S fertiliser sources						
Leaf harvest time	Control	GP10	UNE511	UNE1	TSP+S°f	TSP+S°m	TSP+S°c
			S concentration (%)				
27 DAT	0.20 c	0.25 ab	0.24 b	0.26 ab	0.27 a	0.26 ab	0.27 a
41 DAT	0.13 d	0.14 cd	0.16 bc	0.19 a	0.19 a	0.17 ab	0.18 ab
55 DAT	0.12 c	0.13 c	0.16 b	0.19 a	0.16 abc	0.17 ab	0.16 abc
69 DAT	0.10 c	0.12 bc	0.16 a	0.15 ab	0.13 abc	0.12 bc	0.13 abc
			S content (mg/pot)				
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 with n each harvest time do not differ significantly at the 5% level by DMRT.

averaged over fertilisers was 0.25 and 0.30 mg/pot in the flooded and non-flooded treatments respectively. Application of the different S fertiliser sources did not have any significant effects on S content of leaves at 27 DAT. However, the Control treatment recorded a significantly lower S content compared to the coated fertilisers (Table 3.6). A similar trend was observed at 41 DAT, where the lowest S content of leaves was observed in the Control treatment which was significantly lower than that of GP10 and UNE511 S fertiliser sources. Lower and similar S contents of leaves were recorded in the Control and GP10 treatments at 55 DAT. There were no significant differences in the S content of leaves between the treatments UNE1, TSP+S°f, TSP+S°m and TSP+S°c, and between UNE511 and the three latter fertilisers. At 69 DAT, higher but similar S contents of leaves were recorded in the TSP+S°m and TSP+S°c S fertiliser sources.

(iii) Recovery of fertiliser S in the leaves: Table 3.7 shows the data on the recovery of fertiliser S measured at each leaf harvest under flooded and non-flooded conditions. The Table indicates that at 27 DAT, flooding of the soils significantly increased the mean percentage recovery of the fertilisers from a mean percentage recovery of 18% without flooding to a mean of 41% with flooding. Table 3.7 also shows that the application of the TSP+S°c S fertiliser source resulted in a significantly higher recovery of the fertiliser 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 fertiliser sources. The lowest fertiliser S recovery in the rice leaves was recorded in the UNE511 S fertiliser source.

Table 3.7 Percentage fertiliser S recovery (%) in rice leaves from the different S fertiliser sources measured at each leaf harvest under flooded (F) and non-flooded (NF) conditions.

	S fertiliser sources						
Water regime	GP10	UNE511	UNE1	TSP+S°f	TSP+S°m	TSP+S°c	
				27 DAT			
							Mean
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	
				41 DAT			
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	
				55 DAT			
							Mean
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	
				69 DAT			
							Mean
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.

There was a significant interaction between water regime and S fertiliser source on the percentage fertiliser S recovery in the rice leaves at 41 DAT. That is, in the presence of flood water, most of the fertilisers significantly improved their performance as far as recovery of the fertiliser S is concerned. This is evident in the case of UNE511 and TSP+S°c where flooding of the soils resulted in significantly higher recovery of the respective fertilisers (Table 3.7). At 55 DAT the S fertiliser sources UNE1 TSP+S°f, TSP+S°m and TSP+S°c recorded higher but similar mean percentage of fertiliser S recoveries. Flooding of the soils also significantly increased the mean fertiliser S recovery. A similar trend occurred at 69 DAT, where higher but similar mean fertiliser S recoveries were observed in the S fertilisers UNE1 TSP+S°f, TSP+S°m and TSP+S°c. Application of GP10 and UNE511 resulted in significantly lower mean percentage fertiliser S recovery at 69 DAT.

3.3.4 P Concentration and P Content of Leaves at each Leaf Harvest

(i) Phosphorus concentration in rice leaves: Significant interactions between water regime and S fertiliser source on P concentration in the rice leaves were observed at 27, 41 and 55 DAT. Table 3.8 shows that under flooded conditions, application of GP10 significantly increased P concentration in the rice leaves at 27, 41 and 55 DAT. Generally, however, flooding of the soils significantly influenced the performance of the different S fertiliser sources. At 69 DAT, most of the S fertiliser sources did not have any significant effect on mean P concentration in the rice leaves but the effect of the water regime was significant.

(ii) Phosphorus content of rice leaves: A similar trend as in P concentration was observed with respect to P content of leaves (Table 3.9). There were no significant differences in mean P content of leaves between the different S fertiliser sources at 27 DAT except GP10, which recorded a significantly higher mean P content of leaves with a mean of 0.81 mg/pot. At 41 DAT, a significant interaction between water regime and S fertiliser source on P content of leaves was observed. However, as in the case of P concentration, the performances of the different S fertiliser sources were greatly improved in the presence of flood water. The effects of the application of the different S fertiliser sources on P content of rice leaves were not prominent at 55 and 69 DAT. However, water regime had a significant influence on P content of rice leaves at these days. It is also interesting to note that consistently higher leaf P contents were observed in the GP10 treatment at different leaf harvest times compared to the other S sources, although the differences were not statistically different from some of the S fertiliser sources (Table 3.9).

Table 3.8 Effect of the applications of the different S fertiliser sources on P concentration (%) in the rice leaves at different harvest times under flooded and non-flooded conditions.

	S fertiliser sources							
Water regime	Control	GP10	UNE511	UNE1	TSP+ S°f	TSP+ S°m	TSP+ S°c	
				27 DAT				
F	0.57 c	0.98 a	0.65 bc	0.64 bc	0.66 bc	0.63 bc	0.75 b	
NF	0.21 e	0.37 d	0.32 de	0.35 d	0.35 d	0.33 de	0.30 de	
				41 DAT				
F	0.50 bc	0.67 a	0.54 b	0.47 c	0.50 bc	0.49 bc	0.49 bc	
NF	0.18 e	0.25 d	0.23 de	0.21 de	0.25 d	0.22 de	0.19 de	
				55 DAT				
F	0.42 b	0.53 a	0.40 bc	0.38 bc	0.40 bc	0.39 bc	0.37 c	
NF	0.21 de	0.24 d	0.20 de	0.20 de	0.20 de	0.18 e	0.18 e	
				69 DAT				Mean
F	0.35	0.40	0.47	0.28	0.27	0.26	0.27	0.33 a
NF	0.18	0.18	0.17	0.14	0.15	0.15	0.14	0.16 b
Mean	0.27 ab	0.29 ab	0.32 a	0.21 b	0.21 b	0.21 b	0.21 b	

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

Table 3.9 Effect of the applications of the different S fertiliser sources on P content (mg/pot) of rice leaves at each leaf harvest under flooded and non-flooded conditions.

	S fertiliser sources							
Water regime	Control	GP10	UNE511	UNE1	TSP+ S°f	TSP+ S°m	TSP+ S°c	
				27 DAT				
								Mean
F	0.64	1.20	0.85	0.83	0.82	0.87	0.85	0.87 a
NF	0.23	0.42	0.30	0.32	0.36	0.29	0.31	0.32 b
Mean	0.44 b	0.81 a	0.58 b	0.58 b	0.59 b	0.58 b	0.58 b	
				41 DAT				
F	0.59 d	1.21 a	0.99 b	0.83 c	0.86 bc	0.84 bc	0.88 bc	
NF	0.22 e	0.34 e	0.30 e	0.27 e	0.34 e	0.33 e	0.25 e	
				55 DAT				
								Mean
F	0.71	0.90	0.76	0.78	0.74	0.74	0.76	0.77 a
NF	0.29	0.40	0.37	0.36	0.38	0.34	0.35	0.36 b
Mean	0.50 bc	0.65 a	0.57 ab	0.57 ab	0.56 ab	0.54 ab	0.41 c	
				69 DAT				
								Mean
F	0.58	0.57	0.70	0.55	0.55	0.42	0.53	0.56 a
NF	0.23	0.30	0.29	0.30	0.34	0.28	0.29	0.29 b
Mean	0.41 ab	0.44 ab	0.50 a	0.43 ab	0.45 ab	0.35 b	0.41 ab	

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.

3.3.5 S Concentration, S Content and Recovery of Fertiliser S in the Straw and Grain components

(i) Sulfur concentration in the straw and grain: Application of the different S fertiliser sources resulted in significant differences in mean S concentrations in the straw and grain (Table 3.10). A significantly higher S concentration in the straw was observed in the UNE1 sulfur source, with a mean straw S concentration of 0.071%, but, this did not differ significantly from that in the coated TSP materials with the fine and coarse S° particle sizes. The lowest mean straw S concentrations were observed in the Control and GP10 fertiliser treatments. There was no significant difference in mean straw S concentration between the GP10 and UNE511 S fertiliser sources. The water regimes had a significant effect on mean S concentration in the straw (Table 3.10).

Table 3.10 Sulfur concentration (%) in rice straw and grain as influenced by the application of different S fertiliser sources under flooded and non-flooded conditions.

S fertiliser source	Sulfur concentration (%)					
	Straw			Grain		
	F	NF	Mean	F	NF	Mean
Control	0.043	0.046	0.045 e	0.070	0.073	0.072 d
GP10	0.051	0.047	0.049 de	0.070	0.077	0.073 d
UNE511	0.057	0.054	0.056 cd	0.087	0.070	0.078 cd
UNE1	0.076	0.065	0.071 a	0.103	0.103	0.103 a
TSP+S°f	0.069	0.059	0.064 ab	0.097	0.090	0.093 ab
TSP+S°m	0.058	0.057	0.058 bc	0.087	0.087	0.087 bc
TSP+S°c	0.073	0.062	0.068 a	0.100	0.090	0.095 ab
Mean	0.061 a	0.056 b		0.088 a	0.084 a	

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

In relation to sulfur concentration in the grain, it generally followed a similar trend as the S concentration in the straw (Table 3.10). The highest mean concentration of S in grains was observed in the UNE1 fertiliser treatment, however, as in the case of straw, the mean S concentration in this particular fertiliser treatment was similar to that of the TSP+S° materials with the fine and coarse S° particle sizes. Table 3.10 also shows that the lowest mean grain S concentrations were recorded in the Control, GP10 and UNE511 fertiliser treatments, which were statistically similar to each other. The water regimes did not influence the mean S concentration in the grain (Table 3.10).

(ii) Sulfur content of straw and grain: Flooding of the soils resulted in significant increases in the mean S content of straw and grain (Table 3.11). Application of the different S fertiliser sources resulted in significant differences in the mean S contents of straw and grain, and the mean total S content. Higher mean S contents of straw were recorded in the fertilisers UNE1, TSP+S°f and TSP+S°c, followed by TSP+S°m and UNE511, which were significantly lower as compared to those of the aforementioned S fertiliser sources. The lowest mean S content of straw was observed in the Control treatment, which was significantly lower than that of the GP10 S fertiliser source.

Table 3.11 Effects of the application of the different S fertiliser sources on the S content (mg/pot) of straw and grain, and total S content (straw+grain) under flooded and non-flooded conditions.

	Sulfur content (mg/pot)								
	Straw			Grain			Total		
S material	F	NF	Mean	F	NF	Mean	F	NF	Mean
Control	3.01	3.41	3.21 d	5.00	2.45	3.72 c	8.01	5.86	6.93 e
GP10	6.04	5.60	5.82 c	5.73	3.32	4.52 c	11.77	8.92	10.35 d
UNE511	7.23	6.62	6.93 b	10.51	3.71	7.11 b	17.74	10.33	14.04 c
UNE1	10.25	7.87	9.06 a	12.13	8.20	10.16 a	22.38	16.07	19.22 a
TSP+S°f	9.18	7.44	8.31 a	12.29	6.66	9.48 a	21.47	14.10	17.79 a
TSP+S°m	7.40	6.61	7.00 b	10.57	7.43	9.00 a	17.97	14.04	16.00 b
TSP+S°c	9.70	7.40	8.55 a	12.02	7.82	9.92 a	21.72	15.22	18.47 a
Mean	7.54 a	6.42 b		9.75 a	5.66 b		17.29 a	12.08 b	

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

With regard to mean S content of grain, Table 3.11 indicates that a higher mean S contents of grain were recorded in the S fertiliser sources UNE1, TSP+S°f, TSP+S°m and TSP+S°c, which were similar. The lowest mean S content of grain was observed in the Control and GP10 treatments, which were similar, but significantly lower than that of the UNE511 S fertiliser source.

(iii) Total sulfur content (sum of S content of 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 treatment, but, this did not differ significantly from that of TSP+S°f and TSP+S°c S fertiliser sources (Table 3.11). UNE511 recorded a significantly lower mean total S content in the rice tops, although this was significantly higher than that of the GP10 fertiliser treatment. The lowest mean total S content in the rice tops was observed in the Control treatment.

Generally, the mean total S content in the rice tops was significantly higher under flooded than under non-flooded conditions (Table 3.11).

(iv) Fertiliser S recovery in the straw and grain: Table 3.12 shows the percentage of fertiliser S recovered in the straw and grain. There was no significant water regime x S source interaction on the recovery of fertiliser S in the straw and grain. In relation to the mean percentage of fertiliser S recovery in the straw, Table 3.12 indicates that higher fertiliser S recovered in the straw was recorded in the UNE1 S fertiliser with a mean of 38.6%, although this was not significantly different from those of the TSP+S°f and TSP+S°c fertiliser treatments, but the two latter fertilisers did not differ significantly from that of TSP+S°m. The mean percentages recovery of fertiliser S in the straw were significantly lower in the UNE511 (13.7%) and GP10 (5.6%) S fertiliser sources, which were similar.

The mean percentage recovery of fertiliser S in the grain (Table 3.12) shows a similar trend as has occurred in the case of straw. That is, the application of UNE511 resulted in a lower grain S derived from the respective fertiliser, followed by GP10 which recorded the lowest (4%) recovery.

Table 3.12 Effect of the application of the different S sources on recovery (%) of the fertiliser S in rice straw and grain, and the total recovery of fertliser S in the tops under flooded and non-flooded conditions.

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

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

(v) Total fertiliser S recovery in the rice tops: The total fertiliser S recovery in the rice tops is presented in Table 3.12. Higher but similar mean total fertiliser S recoveries were obtained in the S fertiliser sources TSP+S°c, UNE1 and TSP+S°f with the means of 82.7%, 82.1%

and 68.4%, respectively. There was no significant difference in the mean total fertiliser S recovery between the TSP+S°f and TSP+S°m S sources. The lowest mean total recovery of fertiliser S in the rice tops was observed in the GP10 fertiliser 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 fertiliser S from 38.7% without flooding to 75.4% with flooding.

3.3.6 P Concentration and P Content of Straw and Grain

(i) Phosphorus concentrations in straw and grain: A significantly higher P concentration in the straw was observed in the Control treatment with a mean of 0.26% which was similar to that of GP10 (0.19%) and UNE511 (0.14%) S fertiliser sources (Table 3.13). No significant differences were observed amongst the other S fertiliser sources. Flooding of the soils resulted in a significantly higher P concentration in the straw.

Application of GP10 resulted in a significantly higher P concentration in the grain which was similar to that of the Control treatment (Table 3.13). The lowest P concentration in the grain was recorded in the TSP+S°c fertiliser treatment but this was similar to that of the TSP+S°m S source. There were no significant differences in P concentration between the fertilisers UNE1, TSP+S°f and TSP+S°m, and between UNE511, UNE1 and TSP+S°f. Flooding of the soils significantly increased P concentration in the grain.

Table 3.13 Phosphorus concentration (%) in the straw and grain as influenced by the application of different S fertiliser sources under flooded and non-flooded conditions.

	P concentration (%)					
	Straw			Grain		
S material	F	NF	Mean	F	NF	Mean
Control	0.19	0.09	0.26 a	0.31	0.28	0.30 a
GP10	0.26	0.11	0.19 ab	0.30	0.27	0.29 a
UNE511	0.19	0.37	0.14 ab	0.26	0.24	0.25 b
UNE1	0.18	0.06	0.12 b	0.26	0.22	0.24 bc
TSP+S°f	0.17	0.07	0.12 b	0.26	0.22	0.24 bc
TSP+S°m	0.18	0.06	0.12 b	0.25	0.21	0.23 cd
TSP+S° c	0.17	0.06	0.11 b	0.25	0.20	0.22 d
Mean	0.19 a	0.11 b		0.27 a	0.23 b	

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

(ii) Phosphorus content of straw and grain: There was a significant interaction between water regime and S fertiliser source on P content of straw. Phosphorus content of straw was significantly higher in the GP10 fertiliser treatment in the presence of flood water with a straw P content of 30.9 mg/pot (Table 3.14). In the absence of flood water, GP10 had a significantly higher straw P content which was similar to that of UNE511 S fertiliser source. Generally, however, all treatments had higher straw P contents in the presence of flood water.

There was no significant difference between water regime and S fertiliser source on P content of grain. Table 3.14 shows that both Control and GP10 recorded similar but significantly lower mean P content of grain compared to the other S fertiliser sources. Flooding of the soils significantly increased the mean P content of grain.

Table 3.14 P contents (mg/pot) of straw and grain, and total P content (straw+grain) as influenced by the application of different S fertiliser sources under flooded and non-flooded conditions.

	S fertiliser sources							
Water regime	Control	GP10	UNE511	UNE1	TSP+ S°f	TSP+ S°m	TSP+ S°c	
	P content of straw (mg/pot)							
F	13.0 c	30.9 a	24.0 b	24.5 b	22.2 b	22.4 b	22.0 b	
NF	6.6 e	13.0 c	11.1 cd	7.4 de	8.4 de	6.7 de	7.3 de	
	P content of grain (mg/pot)							Mean
F	22.0	24.5	31.1	30.5	32.6	30.1	29.6	28.6 a
NF	9.1	12.1	12.9	17.1	16.0	17.8	17.0	14.6 b
Mean	15.5 b	18.3 b	22.0 a	23.8 a	24.3 a	23.9 a	23.3 a	
	Total P content of rice tops (mg/pot)							
F	35.0 b	55.4 a	55.1 a	55.0 a	54.8 a	52.5 a	51.6 a	
NF	15.7 d	25.1 c	24.0 c	24.5 c	24.4 c	24.5 c	24.3 c	

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

(iii) Total P content in the rice tops: There was a significant water regime x S source interaction on the total P content of the rice tops. Table 3.14 shows that in the presence of flood water, all of the treatments had higher but similar total P contents of rice tops. The Control treatment, however, recorded the lowest total P content of rice tops in the presence of flood water. It is interesting to note that under flooded conditions, the total P contents in the tops almost doubled compared to the total P contents of rice tops amongst the different S fertiliser sources under non-flooded conditions. That is, the presence of flood water had a significantly positive influence on the performance of the different S fertilisers.

3.3.7 N Concentration and N Content of Straw and Grain

(i) Nitrogen concentration in straw and grain: Table 3.15 shows the N concentration in the straw and grain components. Higher mean straw N concentrations were observed in the Control and the S coated fertilisers UNE511 and GP10, which were statistically similar. The other S fertiliser sources recorded significantly lower mean straw N concentrations and their mean differences did not differ significantly. Water regime had a significant influence on the N concentration in the straw where flooding of the soils resulted in a significantly lower mean N concentration in the straw.

With regard to N concentration in the grain, Table 3.15 shows that a higher mean grain N concentration was recorded in the Control treatment. The S fertiliser sources TSP+S°f, TSP+S°m and TSP+S°c recorded similar but lower mean grain N concentration. Flooding of the soils resulted in a lower mean N concentration in the grain.

(ii) Nitrogen content of straw and grain: Application of UNE511 resulted in a significant increase in the N content of straw with the mean of 94.7 mg N/pot, but this did not differ significantly from that of the GP10 (89.7 mg/pot) and UNE1 (85.1 mg/pot) fertiliser treatments (Table 3.16). No significant differences in mean N content of straw were observed amongst the S fertiliser sources; GP10, UNE1 and TSP+S°f, and amongst UNE1, TSP+S°f, TSP+S°m and TSP+S°c. Water regimes did not influence the mean N content of straw.

With respect to N content of grain, Table 3.16 shows that there were no significant differences in mean N content of grain between the S fertilisers UNE1, UNE511, TSP+S°f, TSP+S°m and TSP+S°c. Application of GP10 resulted in a lower mean grain N content (85.7 mg N/pot), which was similar to the mean N content of grain in the Control treatment. Flooding of the soils significantly increased the mean N content of grain (Table 3.16).

Table 3.15 Effects of the application of the different S fertiliser sources on N concentration (%) in the rice straw and grain under flooded and non-flooded conditions.

	N concentration (%)					
	Straw			Grain		
S fertiliser	F	NF	Mean	F	NF	Mean
Control	0.78	0.84	0.81 a	1.54	1.67	1.60 a
GP10	0.74	0.79	0.76 a	1.32	1.43	1.38 b
UNE511	0.72	0.80	0.76 a	1.23	1.37	1.30 c
UNE1	0.66	0.66	0.66 b	1.08	1.21	1.14 d
TSP+S°f	0.62	0.66	0.64 b	1.02	1.14	1.08 de
TSP+S°m	0.60	0.67	0.64 b	0.99	1.07	1.03 e
TSP+S°c	0.58	0.67	0.63 b	0.95	1.14	1.04 e
Mean	0.67 b	0.73 a		1.16 b	1.29 a	

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

Table 3.16 Effects of the application of the different S fertiliser sources on the N content (mg/pot) of rice straw and grain, and total N content in the rice tops under flooded and non-flooded conditions.

	N content (mg/pot)								
	Straw			Grain			Total		
S fertiliser	F	NF	Mean	F	NF	Mean	F	NF	Mean
Control	53.6	61.6	57.6 d	109.0	55.1	82.0 b	162.6	116.7	139.7 d
GP10	85.9	93.4	89.7 ab	109.2	62.2	85.7 b	195.1	155.6	175.4 c
UNE511	90.8	98.5	94.7 a	149.4	72.5	111.0 a	240.2	171.0	205.6 a
UNE1	89.2	81.0	85.1 abc	126.6	96.1	111.4 a	215.8	177.1	196.5 ab
TSP+S°f	82.6	83.7	83.2 bc	130.0	83.6	106.8 a	212.6	167.3	190.0 abc
TSP+S°m	76.6	79.2	77.9 c	121.1	91.9	106.5 a	197.7	171.1	184.4 bc
TSP+S°c	76.3	80.9	78.6 c	113.7	98.9	106.3 a	190.0	179.8	184.9 bc
Mean	79.3 a	82.6 a		122.7 a	80.0 b		202.0 a	162.7 b	

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

(iii) Total N content in rice tops: The results on the total N content in the rice tops are presented in Table 3.16. The results show that the lowest mean total N content in the rice tops was recorded in the Control treatment, which was significantly lower than that of the GP10 fertiliser treatment. No significant differences in mean total N content in the rice tops were observed between the S fertiliser sources GP10, TSP+S°f, TSP+S°m and TSP+S°c, and between the UNE511, UNE1 and TSP+S°f S fertiliser sources.

3.3.8 Granule strength and dispersion

There was no significant difference in granule strength between products although the range in strength between individual particles varied considerably (Table 3.17).

Table 3.17 Granule strength of the different S fertiliser sources used in the study.

	S fertiliser					
Test No	GP10	UNE511	UNE1	TSP+S° (fine)	TSP+S° (medium)	TSP+S° (coarse)
1	6.6	9.9	10.4	3.9	6.5	4.7
2	6.2	9.4	11.1	6.6	6.1	6.7
3	7.9	10.6	12.5	5.6	7.2	4.7
4	6.6	8.6	8.9	6.4	6.1	4.9
5	6.6	9.6	9.7	5.7	8	4.5
6	5.3	7.2	6.2	5	6.3	5.5
7	4.7	4.8	7.7	6.1	4.8	4.9
8	5.9	6.9	5.3	6.6	7.2	6.2
9	5.9	7.7	9.9	7.1	6.1	4.3
10	4.8	5.4	6.6	5.8	4.7	4.6
11	5.3	6.3	8.5	7.6	7.8	5.6
12	4.7	5.7	6.9	6	7.6	6.2
13	5.9	5.6	6.5	5.6	4.6	5.8
14	5.9	6.4	8.4	6.2	6.2	7.4
15	4.8	4.6	7	4.1	6.9	6.6
16	5.3	6.4	6.8	5.1	7.2	6.2
17	4.7	6.4	7.6	5	5	4.8
18	5.9	6.3	9	7.2	4.8	4.7
19	5.9	5.7	7	5.9	5	6.8
20	4.8	5	9.7	5.5	6.7	4.9
Mean	5.7	6.9	8.3	5.9	6.2	5.5
Standard deviation	0.8	1.8	1.9	1.0	1.1	0.9
Maximum value	7.9	10.8	12.5	7.6	8.0	7.4
Minimum value	4.7	4.6	5.3	3.9	4.6	4.3
Number	20	20	20	20	20	20

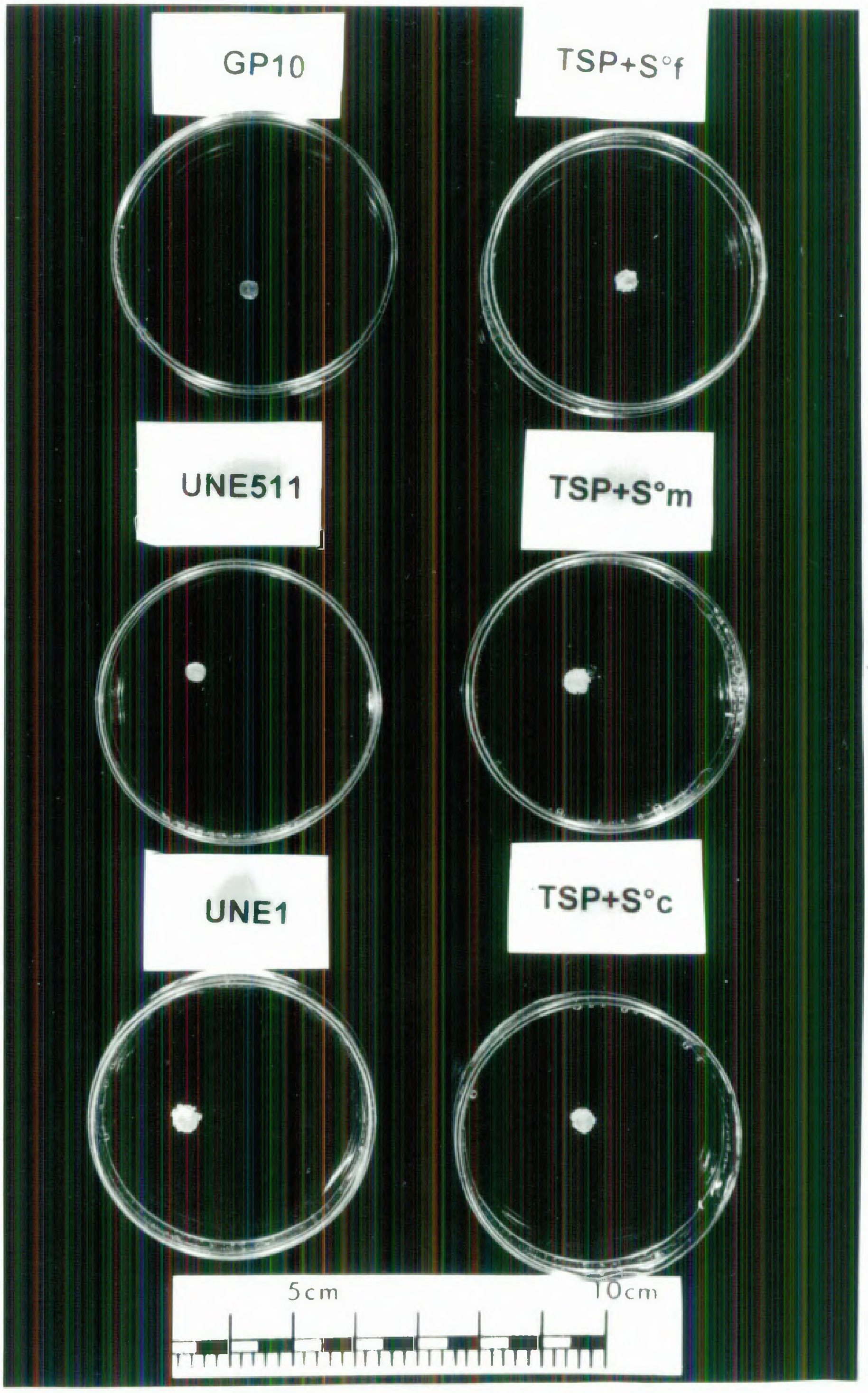

Figure 3.4a Dispersion of the coated fertilisers in distilled water at 0 hours.

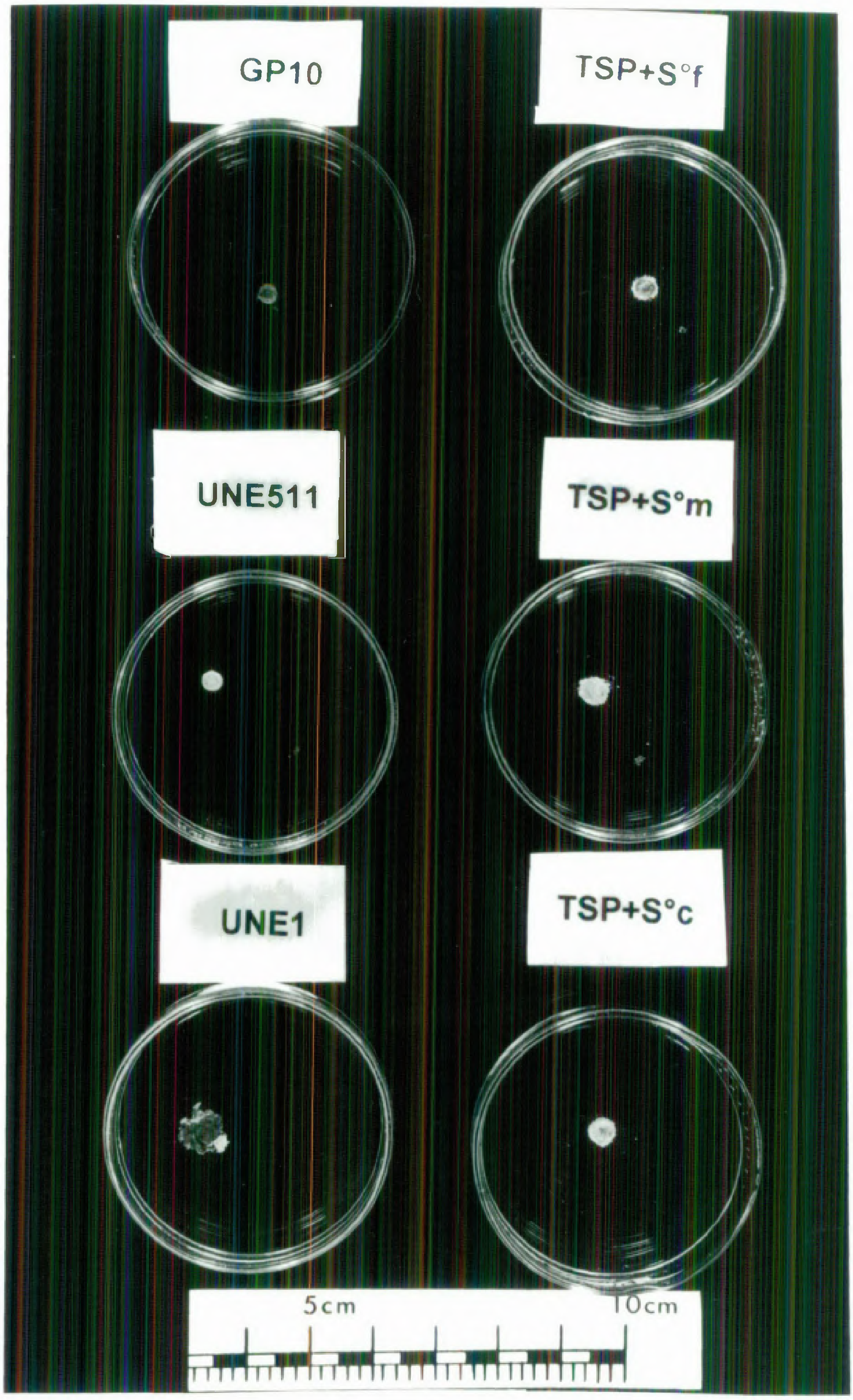

Figure 3.4b Dispersion of the coated fertilisers in distilled water at 24 hours (1 day).

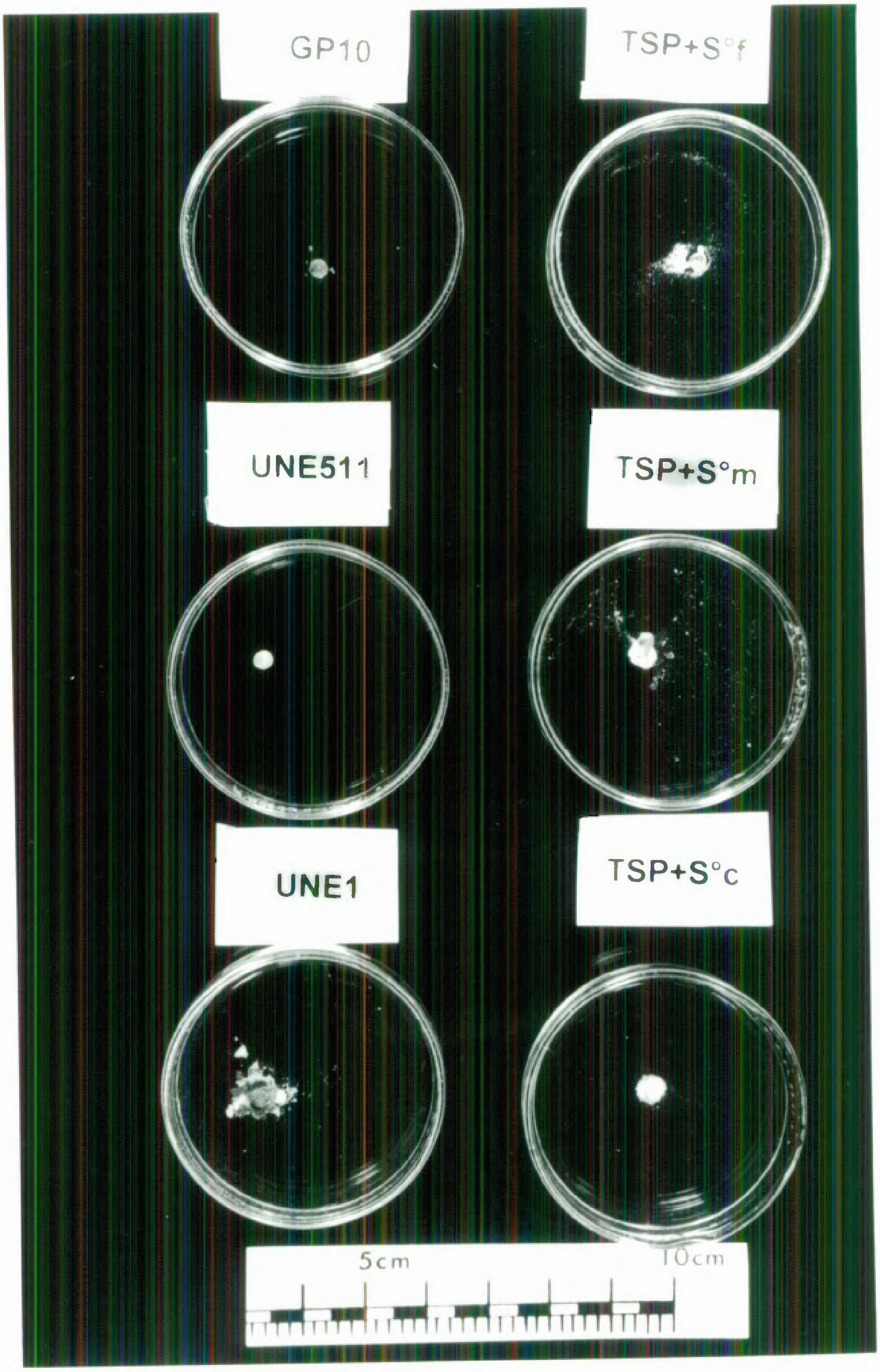

Figure 3.4c Dispersion of the coated fertilisers in distilled water at 72 hours (3 days).

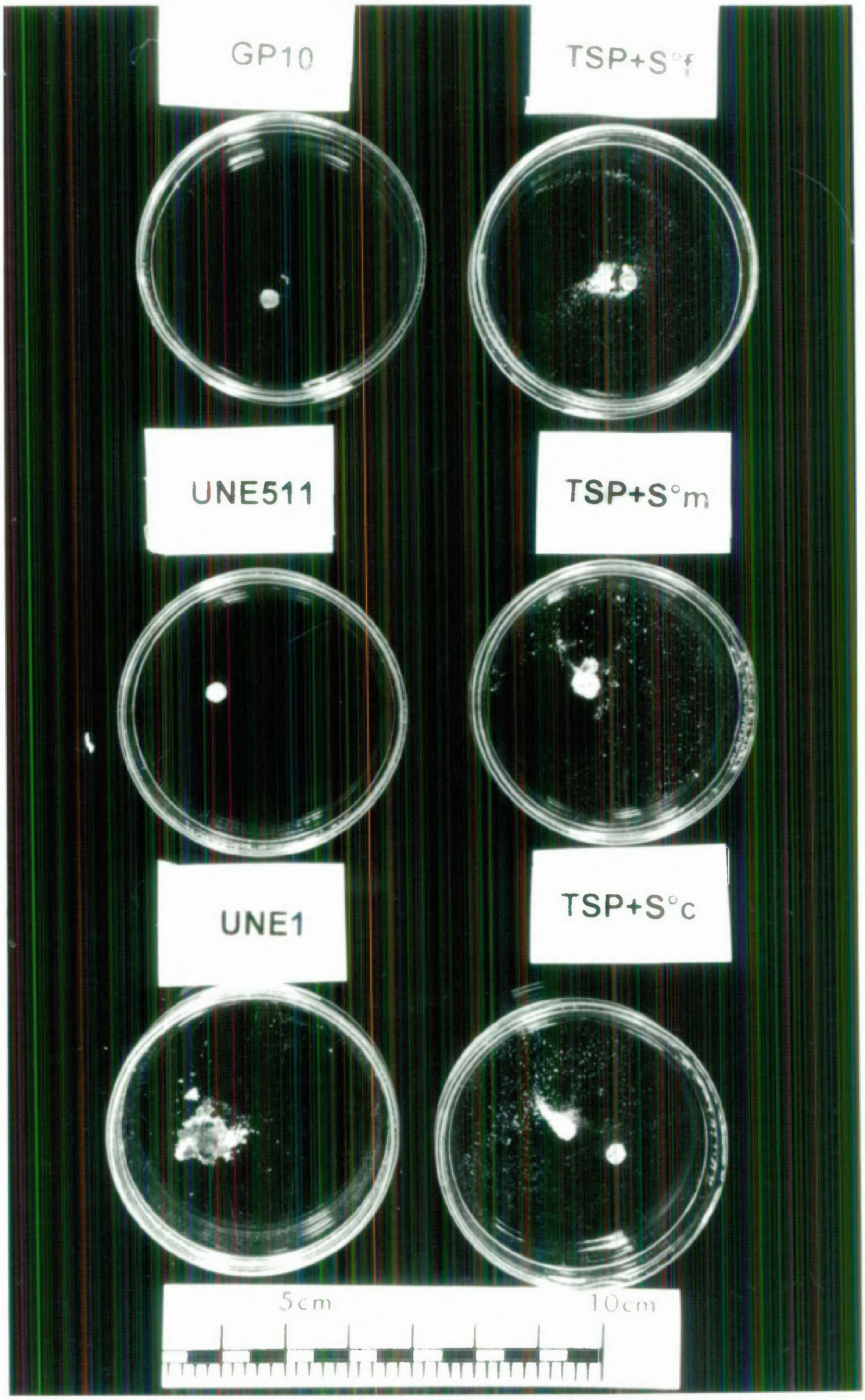

Figure 3.4d Dispersion of the coated fertilisers in distilled water at 120 hours (5 days).

Figures 3.4a, b, c and d indicate the dispersion of the different S fertilisers in distilled water observed at different times. The photographs in Figure 3.4a indicate that when the respective S fertiliser granules were placed in distilled water in a petri-dish, the S fertiliser sources UNE1, TSP+S°f, TSP+S°m and TSP+S°c immediately began to disperse compared to the GP10 and UNE511 S fertiliser sources. At 24 hours, UNE1 disintegrated and dispersed rapidly followed by the TSP+S° products with the fine, medium and coarse S° particle sizes (Figure 3.4b) At 72 hours (3 days) UNE1 almost disintegrated completely (Figure 3.4c) and at 120 hours (5 days), the coat materials of the fertilisers UNE1, TSP+S°f, TSP+S°m and TSP+S°c were almost completely disintegrated and dispersed extensively (Figure 3.4d). However, the GP10 and UNE511 S fertiliser sources failed to disintegrate and disperse significantly. That is, during these times the coats of these fertilisers were still intact as shown by the photographs in Figures 3.4a, b, c and d. These further confirmed the suggestion that these S fertilisers (GP10 and UNE511) released less amount of S compared to the other S fertiliser sources.

3.4 DISCUSSION

3.4.1 Number of Tillers and Grains

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 fertiliser 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 tillers/plant at 27 DAT (Figure 3.1). On the other hand, tiller numbers under non-flooding increased slowly from 2.7 tillers/plant at 20 DAT to 4.6 tillers/plant at 55 DAT. 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, flood water was maintained at a depth of about 4 cm at all times whereas under non-flooded conditions 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. However, despite the lower tiller numbers under the flooded conditions, the filled grain number was significantly higher than under non-flooding (Figure 3.2). 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 3.2), 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 stated 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.

Applications of the different S fertiliser sources under flooding also appears to have contributed to the rapid increase in tiller numbers, thus, higher grain number. Visual observation during the course of the study, showed stunted growth and less tillers in the Control treatment, particularly in the early growth stages (Table 3.3) which are symptoms of S deficiency (Yosida and Chaudhry, 1979; Blair *et al.*, 1979b).

3.4.2 Straw and Grain Yields

Differences in straw yield were largely due to the application of the different S fertiliser sources. Water regimes did not influence straw yield (Table 3.5). Application of GP10 had a significantly lower mean straw yield, although this was similar to that of UNE511, UNE1, TSP+S°m and TSP+S°c fertiliser treatments. Mean grain yields were also lower in the Control and GP10 treatments, followed by UNE511 which recorded a significantly higher grain yield than that of GP10 and the Control treatments. Furthermore, grain yield was greatly increased under flooded than under non-flooded conditions. The data on the total dry weight of tops show that the application of GP10 resulted in a significantly lower mean total dry weight of tops followed by the UNE511 S fertiliser source, which was significantly lower than that of the other S fertiliser sources (Table 3.5). The Control treatment recorded the lowest total dry weight of tops. Similar results were also found by Dana (1992), 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 applications of UNE1 and UNE3 generally gave consistently higher yields irrespective of the water regimes (flooded and non-flooded) employed. In the current study, no significant differences in straw and grain yields amongst the S fertiliser sources UNE1, TSP+S°f, TSP+S°m and TSP+S°c 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. The authors indicated that 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. UNE3 was made in a similar manner, but the binding agent used was calcium lignosulfonate. In the present study, TSP+S°f, TSP+S°m and TSP+S°c were prepared in the similar manner as UNE1 and UNE3, 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 Goldphos by Hi-Fert Pty Ltd (undated), indicates that the Goldphos product (GP10) is made by milling elemental S to an agronomically available size (<250 μm) and chemically bonding it onto TSP granules. The lower straw and grain yields obtained in the Control treatment was largely due to S deficiency. As already indicated above, the application of GP10 and UNE511 resulted in lower mean total dry weight of tops (Table 3.5) and this seems 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 (GP10 and UNE511) 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 did not influence straw yield but grain yield was significantly influenced (Table 3.5). Grain yield under flooded conditions was significantly higher, with a mean of 10.9 g/pot, than that under non-flooded conditions with a mean grain weight of 6.5 g/pot (Table 3.5 and Figure 3.3). This appears to be due mostly to the rapid increase in tiller numbers and early attainment of maximum tillering under flooded conditions (Figure 3.1). Similar results were also reported by Dana *et al.* (1994a) and Ismunadji (1985), who found higher grain yields under flooded 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 flooded and non-flooded conditions was observed. Visual observations during the course of the experiment, showed that under non-flooded conditions, the rice plants were generally shorter but had more tillers, particularly at the later growth stages (41, 55 and 69 DAT) (Figure 3.1). On the other hand, under flooded conditions, the plants were generally taller but had less tillers (Figure 3.1). The non-significant difference in straw yield under these two water regimes may be due to the compensatory effect of higher tiller number under non-flooded and taller plants under flooded conditions. That is, it may have been 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 conditions had less 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 non-flooded conditions.

3.4.3 S Concentration, S Content and Recovery of Fertiliser S in the Leaves, Straw and Grain

Sulfur concentrations in the leaves observed at each leaf harvest were consistently lower in the Control and GP10 treatments, particularly after the first leaf harvest (27 DAT). S concentrations in the leaves in the UNE511 treatment observed at each leaf harvest were significantly higher than that of the Control and GP10 treatments, but generally lower than that of the other S sources at 41 and 55 DAT. At 69 DAT, S concentration in the leaves in the UNE511 fertiliser was similar to that of UNE1, TSP+S°f and TSP+S°c S fertiliser sources. The S content of leaves followed a similar trend as the S concentration in the leaves. Sulfur concentrations and S content of leaves in the Control and GP10 treatments tend to decline with each leaf harvest, whereas with the other S fertiliser sources, S concentration and S content of leaves were generally higher and constant at each leaf harvest (Table 3.6). Similarly, the data on percentage fertiliser S recovery (Table 3.7), indicate that the percentages fertiliser S recovered in the leaves from the GP10 and UNE511 fertilisers were significantly lower at each leaf harvest compared to the other S fertiliser sources. The fact that higher S concentrations and S content of leaves were observed in the GP10 and UNE511 fertilisers at the early growth stages (27 DAT), means that because the rice plants in the early growth stages were relatively smaller, the amounts of S released from the GP10 and UNE511 fertilisers were sufficient to be recovered in the leaves at higher amounts even though they were releasing little S. However, as the rice plants mature the S released from these particular fertilisers was distributed to other leaves or plant parts and because the fertilisers were releasing little S, less amount of fertiliser S was recovered in the leaves, hence, the generally lower S concentrations and S content of leaves at the later growth stages (Table 3.6). On the other hand, the other S sources were able to release higher amounts of S at a sustained level, therefore, the S concentrations, S content of leaves (Table 3.6) and the percentage fertiliser 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 3.7).

The data on S concentrations in the straw and grain (Table 3.10) show that the applications of UNE1, TSP+S°f, TSP+S°m and TSP+S°c fertilisers resulted in significantly higher but similar mean straw and grain S concentrations compared to that of the Control, GP10 and UNE511 treatments. A similar trend was also observed in the case of the mean straw and grain S contents, and the mean total S content of the rice tops (Table 3.11). The lower straw and grain S concentrations, and S contents in the GP10 and UNE511 fertilisers, may be attributed to lack of S as a consequence of little S being released by these fertilisers. Table 3.12 indicates that the mean percentage recovery of fertiliser S in the straw and grain, and the mean total S recovered in the rice tops were significantly lower in the GP10 and UNE511 fertiliser treatments. These results support the view that both GP10 and UNE511 released little S in comparison to the other S fertiliser sources and confirmed the results by Dana *et al.* (1994b), who found that the release of elemental S from UNE1 (polyvinyl alcohol) and UNE3 (Ca lignosulfonate) products were similar and greater than the release from the HF (GP10) product. Blair *et al.* (1994), found a higher amount of fertiliser S recovered in the organic S pool from HF (GP10), and the authors attributed this to the slower S release from HF which resulted in the poor growth of pastures. Moreover, the authors explained that immobilization of S which was released from this product was the main reason for higher S transformation into the organic S fraction.

Tables 3.10, 3.11 and 3.12 show that flooding of the soils significantly increased the straw S concentration, straw and grain S contents and the percentage fertiliser S recovery, respectively. This implies that oxidation of S° was greater under the flooded condition. However, this is in contrast to studies which demonstrated that S° oxidation is favoured at field moisture capacity (Janzen and Bettany, 1987c; Nevell and Wainright, 1987). Nevertheless, 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). In the present experiment, flooding of the soils enhanced most of the S fertilisers, particularly that of UNE1, TSP+S°f, TSP+S°m and TSP+S°c, to disperse faster (Figures 3.4a,b,c and d) thus, releasing most of their S° which were oxidized rapidly by the S oxidizing microorganisms. Furthermore, the results on S concentrations in the straw and grain (Table 3.10) indicate that, although flooding of the soils increased the straw S concentration, the grain S concentration was not influenced. Generally, however, the S concentrations in the grains were higher than in the straw amongst the different treatments. This observation supports the assertion that concentration of S in rice grain is generally higher than in rice straw (Lefroy *et al.*, 1992).

It was highlighted in Chapter 2, that the effectiveness of S° in providing S to crops depends on the rate of oxidation. 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 Tabatabai, 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 current study, no significant differences in straw and grain yields, S concentrations, S contents and fertiliser S recovery in the straw and grain were observed between the different S° particle sizes irrespective of the 2 water regimes used. This indicates that all of them were releasing comparably enough sulfur. This is confirmed by the data on fertiliser S recovery in the leaves (Table 3.7).

3.4.4 P Concentration and P Content of Leaves, Straw and Grain

The data on P concentration in the leaves (Table 3.8) show that leaf P concentrations observed at each leaf harvest were consistently higher in the GP10 treatment under flooded conditions. However, in the final leaf harvest (69 DAT), the Control and UNE511 treatments had similar leaf P concentrations as that of the GP10 fertiliser. Generally, however, all treatments had higher leaf P concentrations in the presence of flood water than in the absence of flood water (Table 3.8). A similar trend was also observed for P content of leaves (Table 3.9). The data on P concentration in the straw and grain (Table 3.13) indicate that the mean P concentration in the straw was significantly higher in the Control which was similar to that of the GP10 and UNE511 fertiliser treatments. A similar trend was observed for grain P concentration. The results on P contents of straw and grain (Table 3.14) show that the mean P content of straw was higher in the GP10 fertiliser treatment. Mean P contents of grain in the GP10 and Control treatments were significantly lower, but the total P content of rice tops was significantly lower only in the Control treatment. Flooding of the soils significantly increased the mean P contents of straw and grain.

This agrees with the generally held view that the P supplying capacity of soil increases following submergence. De Datta (1970), indicated that the P supplying capacity of flooded rice soils is higher than that of upland soils. He further pointed out that flooded rice, in most cases, does not show response to P addition even though upland crops grown on the same soils show a large response. Chang and Chu (1959), found that flooding increased P content in rice by 3 times the increase caused by the application of 44 kg/ha of fertiliser P. These increases in the availability of the soil and fertiliser P under flooding can be attributed to the reduction of ferric phosphate to ferrous phosphate and hydrolysis of Al phosphate (De Datta, 1970). Other mechanisms which contribute to increase P availability in flooded soils include dissolution of organic P in acid soils, increased solubility of Ca phosphate in calcareous soils and greater diffusion of P (Tisdale *et al.*, 1993).

3.4.5 N Concentration and N Content of Straw and Grain

The mean N concentrations in the straw were similar and greater in the Control, GP10 and UNE511 treatments (Table 3.15). The mean N concentration in the grain was higher in the Control treatment, followed by the GP10 which was higher than that of the UNE511 S fertiliser source. The higher N concentrations in the straw and grain in the Control, GP10 and UNE511 treatments is related to the relatively smaller plants in these treatments as a result of lower S supply (Table 3.5). In glasshouse studies, Randall *et al.* (1981) found that N additions decreased wheat yields when the supply of S was suboptimal but doubled yields at high S levels. In the present study, N was applied at 100 kg N/ha at the commencement of the experiment and applied again at 30 and 45 DAT at 40 kg N/ha (total of 180 kg/ha). Despite the adequate supply of N, the mean total dry weight of tops was lower in the Control, GP10 and UNE511 treatments. It is likely that because the supply of S from these treatments was limited, additions of N did not increase the mean total yield of rice tops compared to that of the UNE1, TSP+S°f, TSP+S°m and TSP+S°c S fertiliser sources. Moreover, flooding of the soils resulted in lower mean straw and grain N concentrations (Table 3.15). This may be due to the fact that flooding of the soils restricted nitrification (Mengel and Kirkby, 1987). Ponnamperuma (1965) reported that submerged soils are particularly susceptible to denitrification. Nitrogen concentration in the straw and grain was multiplied by the dry weight of straw and grain, respectively, to give the N content per pot. The data on N contents of straw and grain (Table 3.16) indicate significantly lower mean N contents of straw and grain in the Control treatment. However, although N contents of straw was higher in the GP10 fertiliser, the mean grain N content was lower. The data on mean total N content (Table 3.16) indicate that UNE511, UNE1 and TSP+S°f recorded higher but similar mean total N content of rice tops.

It has been shown previously that the total dry weight of tops was lower in the Control, GP10 and UNE511 treatments, in that order, (Table 3.5). Lower rice growth and yield are some of the symptoms of S deficiency (Blair *et al.*, 1979a). According to Ergle and Eaton (1951), in cotton, the percentage of total N was always greater when the sulfate supply limited growth and they observed that where there were lower S levels (both SO_4^{2-} and soluble organic S) in cotton leaves, an accumulation of non-protein N occurred, particularly that of NH_2 and NO_3^- - N. The authors, however, observed that the high accumulations of NO_3^- and soluble organic N found at low sulfate levels gave way to an accumulation of protein N at the higher sulfate levels. A study on nitrogen-sulfur relationships in wheat, corn and beans (Stewart and Porter, 1969), showed that when S became limiting, the non protein N (nitrates, amides, and amino acids) increased. Also, studies on alfalfa (*Medicago sativa*) by Rendig and McComb (1961), indicated that amides accumulated when S was limiting. Similar results were reported by Adams and Sheard (1966), who found large accumulations of amide-N in both alfalfa and orchardgrass (*Dactylis glomerata*) when S was limiting. Furthermore, in corn plants, Terman *et al.* (1973), observed that highest N/S ratios would occur at the minimum S concentration when S was a limiting nutrient, and the lowest at the minimum N concentration when N was a limiting nutrient. In the current study, N concentrations in the straw and grain were high in the Control, GP10 and UNE511 treatments (Table 3.15), which recorded low mean straw and grain S concentrations and S contents, and mean total S content of rice tops (Tables 3.10 and 3.11).

3.4.6 Comparison of the different S Coated Fertiliser Sources

In general, the results in the current study clearly demonstrated that amongst the S coated fertiliser sources, UNE1 and the TSP+S° products with the fine, medium and coarse S° particle sizes were more effective than the other sources. This was due primarily to the use of water-soluble adhesives (polyvinyl alcohol and Ca lignosulfonate) to bind S° 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 excessively warm air and vigorous rotation during its preparation, the coat was extra hard which tended to impede water penetration into the granules and the consequent dispersion of S° into the soil. The application of GP10 also generally resulted in poorer S response than UNE1 and the TSP+S° products. It has been highlighted previously that this particular product was prepared by milling S° 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° into the soil. Table 3.17 presents the results of the granule strength of the different S fertiliser sources. The data show that although the mean granule strength of UNE1 was higher than that of the other S sources, it was able to break up and dispersed rapidly, which was similar to the TSP+S° products with the fine, medium and coarse S° particle sizes as shown by the photographs in Figures 3.4a, b, c and d. On the other hand, both GP10 and UNE511 had lower mean granule strengths than that of UNE1 but almost similar to that of the TSP+S° products with the fine, medium and coarse S° particle sizes. Nevertheless, they (GP10 and UNE511) were unable to disintegrate and disperse rapidly (Figures 3.4a, b, c and d). This demonstrates that granule strength was not a major factor contributing to the impairment of water penetration into the granules of these fertilisers. It seems probable that during the production process, the water-soluble characteristics of the coat material of the GP10 and UNE511 fertilisers may have been altered and made impervious thereby impeding water penetration into the granules.

The rate of nutrient release from slow release fertilisers has been 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; Lunt, 1971). Kochba *et al.* (1990), proposed that the mechanism responsible for nutrient release is the diffusion of water vapour into the granule through the hydrophobic membrane (coat material) and the subsequent bursting or expansion of the membrane, which leads 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 behaviour showed that individual granules within a given population of a slow-release fertiliser have different release patterns. 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 fertiliser 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 fertiliser granules, the water-soluble nature or characteristics of the coat material should be maintained so that water penetration into the granules, which is the beginning of the entire process of fertiliser nutrient release, can not be impeded.

3.5 CONCLUSION

On the basis of these results, it is apparent that UNE1, TSP+S°f, TSP+S°m and TSP+S°c are effective S fertiliser sources for rice under flooded and non-flooded conditions compared to GP10 and UNE511 S fertiliser sources. It is also evident that the use of water-soluble adhesives such as polyvinyl alcohol and calcium lignosulfonate to bind S° 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. This was clearly exhibited by the

UNE511 S fertiliser source, wherein although it had the same coating material as UNE1, it failed to perform comparably due to being subjected to excessively warm air and vigorous rotation during its preparation. Therefore, it may be necessary for any future study to investigate this aspect of the coating process in an effort to clearly determine a suitable temperature regime for the different coating materials used.

Furthermore, the fact that some authors attributed different responses to the coating thickness needs to be further examined to ascertain whether the coat thickness, for example that of UNE1 (polyvinyl alcohol) or the TSP+S° products (Ca lignosulfonate), is directly responsible for the effectiveness of the S fertiliser sources. The use of the different S° particle sizes did not have any dramatic effect in the present study. It would be beneficial in the future to look at the use of different sulfur particle sizes and rates so that not only an "agronomically acceptable" S° particle size can be achieved, but also the optimum rate at which this can be applied to obtain optimum benefits as suitable S fertiliser sources for rice under flooded and non-flooded conditions.

REFERENCES

Achorn, F.P., and Cox, T.R. (1971). Production, Marketing, and use of solid, solution, and suspension fertilizers. *In* Olson, R.A., Army, T.J., Hanway, J.J., and Kilmer, V.J. (eds.), *Fertilizer Technology and Use. 2nd edition*. Soil Sci. Soc. Am., Madison, WI. pp 381-412.

Adams, C.A., and Sheard, R.W. (1966). Alterations in the nitrogen metabolism of *Medicago sativa* and *Dactylis glomerata* as influenced by potassium and sulfur nutrition. *Canadian Journal of Plant Science* **46** 671-680.

Ahmed, I.U., Attoe, O.J., Engelbert, L.E., and Corey, R.B. (1963). Factors affecting the rate of release of fertilizers from capsules. *Agronomy Journal* **55**, 495-499.

Allison, F.E. (1973). Soil organic matter and its role in crop production. Elsevier, Amsterdam.

Alston, A.M., and Chin, K.W. (1974). Response of subterranean clover to rock phosphates as affected by particle size and depth of mixing in the soil. *Australian Journal of Experimental Agriculture and Animal Husbandry* **14**, 649-655.

Anderson, G.C. (1988). Dissolution of rock phosphate in soil, plant and fertiliser systems. M.Ru.Sc. Thesis. The University of New England, Armidale.

Anderson, J.W. (1975). The function of sulphur in plant growth and metabolism. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture.* Sydney University Press, Sydney; Australia. pp 87-97.

Anderson, D.L., and Henderson, L.J. (1986). Sealed chamber digestion for plant nutrient analysis. *Agronomy Journal* **78**, 937-938.

Aylmore, L.A.G., Karim, M., and Quirk, J.P. (1967). Adsorption and desorption of sulfate ions by soil constituents. *Soil Science* **103**, 10-15.

Barber, S.A., Munson, R.D., and Dancy. W.B. (1971). Production, marketing, and use of potassium fertilizers. *In* Olson, R.A., Army, T.J., Hanway, J.J., and Kilmer, V.J. (eds.), *Fertilizer Technology and Use. 2nd edition.* Soil Sci. Soc. Am., Madison, WI. pp 303-334.

Barrow, N.J. (1960). A comparison of the mineralization of nitrogen and of sulphur decomposing organic materials. *Australian Journal of Agricultural Research* **11**, 960-969.

Barrow, N.J. (1961). Studies on mineralization of sulphur from soil organic matter. *Australian Journal of Agricultural Research* **12**, 306-319.

Barrow, N.J. (1971). Slowly available sulphur fertilizers in south-western Australia: 1. Elemental sulphur. *Australian Journal of Experimental Agriculture and Animal Husbandry* **11**, 211-216.

Beaton, J.D. (1987). Desirable characteristics of sulphur containing fertilizers suitable for Asia and the Pacific region. *Proceedings of the Symposium on Fertilizer Sulphur Requirements and Sources in Developing Countries of Asia and the Pacific.* Bangkok, 26-30 Jan., 1987. pp 101-111 FADINAP, FAO, The Sulphur Inst., ACIAR.

Beaton, J.D., and Fox, R.L. (1971). Production marketing and use of sulfur products. *In* Olson, R.A., Army, T.J., Hanway, J.J., and Kilmer, V.J. (eds.), *Fertilizer Technology and Use. 2nd edition.* Soil Sci. Soc. Am., Madison, WI. pp 335-379.

Beaton, J.D., and Soper, R.J. (1986). Plant response to sulfur in Western Canada. *In* Tabatabai, M.A. (ed.), *Sulfur in Agriculture.* Agronomy Monograph No.27, Madison, WI. pp 375-403.

Bettany, J.R., Saggar, S., and Stewart, J.W.B. (1980). Comparison of the amounts and forms of sulfur in soil organic matter fractions after 65 years of cultivation. *Soil Science Society of America Journal* **44**, 70-75

Bettany, J.R., Stewart, J.W.B., and Halstead, E.H. (1973). Sulfur fractions and carbon, nitrogen and sulfur relationships in grassland, forest and associated transitional soils. *Soil Science Society of America Proceedings* **37**, 915-918.

Bixby, D.W., and Kilmer, V.J. (1975). Sulphur resources available to the fertilizer industry, the fertilizers made, their role and the problems involved in their manufacture. *In* McLachlan. K.D. (ed.), *Sulphur in Australasian Agriculture.* Sydney University Press, Sydney; Australia. pp 231-241.

Blair, G.J. (1979). Sulfur in the Tropics. Technical Bulletin. IFDC-T12. International Fertilizer Development Center, Muscle Shoals, Alabama, USA.

Blair, G.J. (1983). Sulfur deficiencies in the agriculture of Southern China. *In* Blair, G.J., and Till, A.R. (eds.), *Sulfur in South East Asian and South Pacific Agriculture.* Indonesia. UNE. pp 147-154.

Blair, G.J. (1984). Sulphur fertiliser sources for upland and flooded rice soils of the tropics. *Proceedings of Sulphur-84*, Alberta, Canada, 3-6 June, pp 717-723. Sulphur Dev. Inst., Canada (SUDIC), Calgary, Canada.

Blair, G.J., Dana, M., and Lefroy, R.D.B. (1994). A glasshouse evaluation of sulfur fertiliser sources for crops and pastures. II. A comparison of sulfur coated triple superphosphates and gypsum. *Australian Journal of Agricultural Research* **45**, 1517-1523.

Blair, G.J., and Lefroy, R.D.B. (1987). Sulphur cycling in tropical soils and the agronomic impact of increasing use of S free fertilizers, increased crop production and burning of crop residues. *Proceedings of the Symposium on Fertilizer Sulphur Requirements and Sources in Developing Countries of Asia and the Pacific.* Bangkok, 26-30 Jan., 1987. pp 12-17 FADINAP, FAO, The Sulphur Inst., ACIAR.

Blair, G.J., Mamaril, C.P., and Momuat, E. (1978). Sulfur nutrition of wetland rice. IRRI Res. Paper Series No.21. International Rice Research Institute, Philippines.

Blair, G.J., Mamaril, C.P., Pangerang Umar, A., Momuat, E.O., and Momuat, C. (1979a). Sulfur nutrition of rice. I. A survey of soils of South Sulawesi, Indonesia. *Agronomy Journal* **71**, 473-477.

Blair, G.J., Momuat, E.O., and Mamaril, C.P. (1979b). Sulfur nutrition of rice. II. Effect of source and rate of S on growth and yield under flooded conditions. *Agronomy Journal* **71**, 477-480.

Blair, G.J., and Sale, P. (1996). *Plant Nutrition: Feeding the Plant-Sustaining the Soil.* University of New England, Armidale; Australia.

Blair, G.J.. and Till, A.R. (1981). Sulfur in Southeast Asia. *Sulfur in Agriculture* **5**, 5-11.

Bloomfield, C. (1967). Effect of some phosphate fertilisers on the oxidation of elemental sulfur in soil. *Soil Science* **103**, 219-223.

Boswell, C.C. (1987). Elemental sulphur fertilisers in New Zealand. *International Symposium on Elemental sulphur in Agriculture, Proceedings.* Volume 2, Acropolis. Nice, France, March 25-27, 1987 pp 493-507 (Syndicat Francais du Soufre: Marseille).

Boswell, C.C., and Friesen, D.K. (1993). Elemental sulfur fertilisers and their use on crops and pastures. *Fertilizer Research* **35**, 127-149.

Boswell, C.C., Swanney, B., and Braithwaite, A.C. (1996). The effects of different manufacturing techniques on the availability of sulfate to pasture from mixtures of elemental sulfur with either triple superphosphate or partially acidulated reactive phosphate rock. *Fertilizer Research* **44**, 225-263.

Boswell, C.C., Swanney, B., and Owers, W.R. (1988). Sulfur/sodium bentonite prills as sulfur fertilisers. 2. Effect of sulfur-sodium bentonite ratios on the availability of sulfur to pasture plants in the field. *Fertilizer Research* **15**, 33-46.

Burns, G. (1968). *Oxidation of sulfur in soils.* The Sulfur Institute, Washington, D.C. Technical Bulletin No: 13, pp 1-40.

Burr, E.J. (1982). NEVA User's Manual. Analysis of variance for complete factorial experiments. The University of New England, Armidale, NSW.

Chaitep, W. (1990). The use of fertilisers and crop residues as sources of sulfur in flooded and unflooded rice cropping systems. Ph.D Thesis. The University of New England, Armidale, NSW, Australia.

Chang, S.C., and Chu, W.K. (1959). Radioactive assay of the availability of soil phosphorus in the lowland rice soils. *Proceedings of the Third Conference on Radioisotope.* Japan. pp 936-961.

Chapman. S.J. (1989). Oxidation of micronized elemental sulphur in soil. *Plant and Soil* **16**. 69-76.

Chapman, S.J. (1997a). Barley straw decomposition and S immobilization. *Soil Biology and Biochemistry* **29**, 109-114.

Chapman, S.J. (1997b). Carbon substrate mineralization and sulphur limitaion. *Soil Biology and Biochemistry* **29**, 115-122.

Chaudhry, I.A., and Cornfield, A.H. (1967a). Effect of moisture content during incubation of soil treated with organic materialson changes in sulphate and sulphide levels. *Journal of the Science of Food and Agriculture* **18**, 38-40.

Chaudhry, I.A., and Cornfield, A.H. (1967b). Effect of temperature of incubation on sulphate levels in aerobic and sulphide levels in aenorobic soils. *Journal of the Science of Food and Agriculture* **18**, 82-84.

Chien, S.H., Hellums, D.T., and Henao, J. (1987). Greenhouse evaluation of elemental sulfur and gypsum for flooded rice. *Soil Science Society of America Journal* **51**, 120-123.

Chinoim, N. (1994). Soil sulfur pools utilized by plants and measured by chemical extractants. Ph.D Thesis. University of New England, Armidale.

Cifuentes, F.R., and Lindemann, W.C. (1993). Organic matter stimulation of elemental sulfur oxidation in a calcareous soil. *Soil Science Society of America Journal* **57**, 727-731.

Dana, M. (1992). Sulfur sources for flooded and non flooded rice and pastures. Ph.D Thesis. University of New England, Armidale.

Dana, M., Lefroy, R.D.B., and Blair, G.J. (1994a). A glasshouse evaluation of sulfur fertiliser sources for crops and pastures. I. Flooded and non-flooded rice. *Australian Journal of Agricultural Research* **45**, 1497-1515.

Dana, M., Lefroy, R.D.B., and Blair, G.J. (1994b). A glasshouse evaluation of sulfur fertiliser sources for crops and pastures. IV. Water solubility and physical losses and sulfur and phosphorus from S-coated triple superphosphates. *Australian Journal of Agricultural Research* **45**, 1539-1545.

Dear, B.S., and Spencer, K. (1982). The effectiveness of several fertiliser in supplying sulfur to temperate pastures. *Australian Journal of Experimental Agriculture and Animimal Husbandry* **22**, 412-419.

De Datta, S.K. (1970). Fertilizers and soil amendments for tropical rice. *In* 'Rice Production Manual'. University of the Philippines/IRRI. pp 106-146.

De Datta, S.K., Levine, G., and Williams, A (1970). Water management practices and irrigation requirements for rice. *In* 'Rice Production Manual'. University of the Philippines/IRRI. pp 89-95.

Ergle, D.R., and Eaton, F.M. (1951) Sulphur nutrition of cotton. *Plant Physiology* **26**, 639-654.

Evans, L.T. (1975). Sulphur in agriculture. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture.* Sydney University Press, Sydney; Australia. pp 3-8.

Fenster, W.E. (1965). M.S. Thesis. University of Wisconsin. Cited by Weir, R.G. (1975).

Fisher, F.L., Cantwell, D., and Mathiesen, G.C. (1984). Dry and flowable elemental sulphur and thiosulfate in fertilisers. *Proceedings of Sulphur-84*, Alberta, Canada, 3-6 June, pp 845-850. Sulphur Dev. Inst., Canada (SUDIC), Calgary, Canada.

Fox, R.L., Atesalp, H.M., Kampbell, D.H., and Rhoades, H.F. (1964). Factors influencing the availability of sulfur fertilisers to alfalfa and corn. *Soil Science Society of America Proceedings* **28**, 406-408.

Freney, J.R. (1961). Some observations on the nature of organic sulphur compounds in soil. *Australian Journal of Agricultural Research* **12**. 424-432.

Freney, J.R. (1986). Forms and reactions of organic sulfur compounds in soils. *In* Tabatabai, M.A. (ed.), *Sulfur in Agriculture.* Agronomy Monograph No. 27, Madison, Wisc., USA. pp 207-232.

Freney, J.R., and Boonjawat, J. (1983). Sulfur transformations in wetland soils. *In* Blair, G.J., and Till, A.R. (eds.), *Sulfur in South East Asian and South Pacific Agriculture.* Indonesia. UNE. pp 28-38.

Freney, J.R., Jacq, V.A., and Baldensperger F.J. (1982). The significance of the biological sulfur cycles in rice production. *In* Dommergues, Y.R., and Diem, H.G. (eds.), *Microbiology of Tropical Soils and Plant Productivity*. pp 271-317. Martinus Nijhoff/Dr W Junk Publisher, The Hague.

Freney, J.R., and Spencer, K. (1960). Soil sulphate changes in the presence and absence of growing plants. *Australian Journal of Agricultural Research* **11**, 339-345.

Freney, J.R., and Swaby, R.J. (1975). Sulphur transformations in soils. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture*. Sydney University Press, Sydney; Australia. pp 31-39.

Friesen, D.K. (1991). Fate and efficiency of sulfur fertilizer applied to food crops in West Africa. *Fertilizer Research* **29**, 35-44.

Friesen, D.K. (1996). Influence of co-granulated nutrients and granule size on plant responses to elemental sulfur in compound fertilisers. *Nutrient Cycling in Agroecosystems* **46**, 81-90.

Germida, J.J., and Janzen, H.H. (1993). Factors affecting the oxidation of elemental sulfur in soils. *Fertilizer Research* **35**, 101-114.

Ghani, A., McLaren, R.G., and Swift, R.S. (1992). Sulphur mineralization and transformations in soils as influenced by additions of carbon, nitrogen and sulphur. *Soil Biology and Biochemistry* **24**, 331-341.

Grayston, S.J., Nevell, W., and Wainwright, M. (1986). Sulphur oxidation by fungi. *Transactions of the British Mycological Society* **87**, 193-198.

Grist. D.H. (1986). *Rice*. Sixth edition. Longman Group Limited, London.

Gupta, U.C., and MacLeod, J.A. (1984). Effect of various sources of sulfur on yield and sulfur concentration of cereals and forages. *Canadian Journal of Soil Science* **64**, 403-409.

Hagstrom, G.R. (1986). Fertilizer sources of sulfur and their use. *In* Tabatabai, M.A. (ed.), *Sulfur in Agriculture*. Agronomy Monograph No.27. Madison, Wisc. USA. pp 567-581.

Hi-Fert Pty Ltd (undated). *Gold-Phos.* Bulletin No.8. 13 pp.

Hoeft, R.G., and Walsh, L.M. (1975). Effect of carrier, rate and time of application of S on the yield, and S and N content of alfalfa. *Agronomy Journal* **67**, 427-430.

Hoult, E., Andrews, A., and Keerati-Kasikorn, P. (1983). Sulfur deficiencies in the agriculture of Thailand, Kampuchea, Laos and Vietnam. *In* Blair, G.J., and Till, A.R. (eds.), *Sulfur in South East Asian and South Pacific Agriculture.* Indonesia. UNE. pp 115-146.

IRRI (1995). *Program Report for 1994.* International Rice Research Institute, Los Baños, Laguna, Philippines.

Ismunadji, M. (1985). Effect of sulfate application on the performance of IR36 rice variety under submerged and dry land conditions. *Indonesian Journal of Crop Science* **1**, 21-28.

Ismunadji, M., Blair, G.J., Momuat, E., and Sudjadi, M. (1983). Sulfur in the agriculture of Indonesia. *In* Blair, G.J., and Till, A.R. (eds.), *Sulfur in South East Asian and South Pacific Agriculture.* Indonesia. UNE. pp 165-179.

Janzen, H.H. (1990). Elemental sulfur oxidation as influenced by plant growth and degree of dispersion within soil. *Canadian Journal of Soil Science* **70**, 499-502.

Janzen, H.H., and Bettany, J.R. (1986) Release of available sulfur from fertilisers. *Canadian Journal of Soil Science* **66**, 91-103.

Janzen, H.H., and Bettany, J.R. (1987a). Oxidation of elemental sulfur under field conditions in Central Saskatchewan. *Canadian Journal of Soil Science* **67**, 609-618.

Janzen, H.H., and Bettany, J.R. (1987b). Measurement of sulfur oxidation in soils. *Soil Science* **143**, 444-452.

Janzen, H.H., and Bettany, J.R. (1987c). The effect of temperature and water potential on sulfur oxidation in soils. *Soil Science* **144**, 81-89.

Joffe, J.S., and McLean, H.C. (1922). A note on oxidation of sulfur in Oregon soils. *Soil Science* **14**, 217-221.

Jones, M.B. (1984). Effects of fertilizer sources of sulphur on plant growth and sulphur uptake. *Proceedings of Sulphur-84*, Alberta, Canada. 3-6 June, Sulphur Dev. Inst., Canada (SUDIC), Calgary, Canada. pp 711-716.

Jones, M.B., Martin, W.E., and Williams, W.A. (1968). Behavior of sulfate sulfur and elemental sulfur in three California soils in lysimeters. *Soil Science Society of America Proceedings* **32**, 535-540.

Jones, M.B., and Ruckman, J.E. (1966). Gypsum and elemental sulfur as fertilisers on annual grassland. *Agronomy Journal* **58**, 409-412.

Kittams, H.A. (1965). Use of sulfur for increasing the availability of phosphorus in rock phosphate. Ph.D. Thesis. University of Wisconsin. Cited by Samosir, S.S.R. (1981).

Kittams, H.A., and Attoe, O.J. (1965). Availability of phosphorus in rock phosphate-sulfur fusions. *Agronomy Journal* **57**, 331-334.

Kochba, M., Ayalon, O., and Avnimelech, Y. (1994). Slow release rate: Individual granules and population behaviour. *Fertilizer Research* **39**, 39-42.

Kochba, M., Gambash, S., and Avnimelech, Y. (1990). Studies on slow release fertilisers: 1. Effects of temperature, soil moisture, and water vapor pressure. *Soil Science* **149**, 339-343.

Koehler, F.E., and Roberts, S. (1983). An evaluation of different forms of sulphur fertilisers. *In* More, A.I. (ed.), *Proceedings of the International Sulphur-82 Conference*. **2**: pp 833-841. The British Sulphur Corporation Limited, London.

Konishi, Y., Asai, S., and Yoshida, N. (1995). Growth kinetics of *Thiobacillus thiooxidans* on the surface of elemental sulfur. *Applied and Environmental Microbiology* **61**, 3617-3622.

Konopka, A.E., Miller, R.H., and Sommers, L.E. (1986). Microbiology of the sulfur cycle. *In* Tabatabai, M.A. (ed.), *Sulfur in Agriculture.* Agronomy Monograph No. 27, Madison, Wisc. USA. pp 23-55.

Kowalenko, E.A., and Baptie, R.S. (1984). Sulphur in agriculture. *Proceedings of Sulphur-84*, Alberta, Canada, 3-6 June, pp 835-839. Sulphur Dev. Inst., Canada (SUDIC), Calgary, Canada.

Krouse, H.R., and McCready, R.G.L. (1979). Biogeochemical cycling of sulfur. *In* Trudinger, P.A., and Swaine, D.J. (eds.), *Studies in Environmental Science* **3**. *Biogeochemical Cycling of Mineral-Forming Elements.* Elsevier Scientific. Amsterdam. pp 401-430.

Lawrence, J.R., and Germida, J.J. (1988). Relationship between microbial biomass and elemental sulfur oxidation in agricultural soils. *Soil Science Society of America Journal* **52**, 672-677.

Lawton, K., Apostolakis, C., Cook, R.L., and Hill, W.L. (1956). Influence of particle size, water solubility, and placement of fertilisers on the nutrient value of phosphorus in mixed fertilisers. *Soil Science* **82**, 465-475.

Lee, A., Watkinson, J.H., and Lauren, D.R. (1988). Factors affecting oxidation rates of elemental sulfur in a soil under a ryegrass dominant sward. *Soil Biology and Biochemistry* **20**, 809-816.

Lee, A., Watkinson, J.H., Orbell, G., Bagyaraj, J , and Lauren, D.R. (1987). Factors influencing dissolution of phosphate rock and oxidation of elemental sulphur in some New Zealand soils. *New Zealand Journal of Agricultural Research* **30**, 373-385.

Lefroy, R.D.B., Mamaril, C.P., Blair, G.J., and Gonzales, P.J. (1992). Sulphur cycling in rice wetlands. *In* Howarth, R.W., Stewart. J.W.B., and Ivanov, M.V. (eds.), *SCOPE 48. Sulphur Cycling on other Continents: Wetlands, Terrestrial Ecosystems and Associated Water Bodies.* John Wiley and Sons Ltd. England. pp 279-300.

Lefroy, R.D.B., Sholeh, and Blair, G.J. (1997). Influence of sulfur and phosphorus placement, and sulfur particle size, on elemental sulfur oxidation and the growth response of maize (Zea mays). *Australian Journal of Agricultural Research* **48**, 485-495

Li, P., and Caldwell, A.C. (1966). The oxidation of elemental sulfur in soil. *Soil Science Society of America Proceedings* **30**, 370-372.

Lindemann, W.C., Aburto, J.J., Haffner, W.M., and Bono, A.A. (1991). Effect of sulfur source on sulfur oxidation. *Soil Science Society of America Journal* **55**, 85-90.

Loganathan, P., Hedley, M.J., and Clark, S.A. (1992). The manufacture and evaluation of granular potassium chloride fertilisers. *Fertilizer Research* **31**, 291-304.

Lunt, O.R. (1971). Controlled-release fertilizers: Achievements and potential. *Journal of Agriculture and Food Chemistry* **19**, 797-800.

Lunt, O.R., and Oertli, J.J. (1962). Controlled release of fertilizer minerals by encapsulating membranes: II. Efficiency of recovery, influence of soil moisture, mode of application, and other considerations related to use. *Soil Science Society of America Proceedings* **26**, 584-587.

Mamaril, C.P., and Gonzalez, P.B. (1987). Sulphur status and requirements of the Philippines. *Proceedings of the Symposium on Fertilizer Sulphur Requirements and Sources in Developing Countries of Asia and the Pacific.* Bangkok, 26-30 Jan., 1987. pp 67-75 FADINAP, FAO, The Sulfur Inst., ACIAR.

Mamaril, C.P., Villapande, R.R., and Bunoan J.C. (1983). Sulfur in the agriculture of the Philippines. *In* Blair, G.J., and Till, A.R. (eds.), *Sulfur in South East Asian and South Pacific Agriculture.* Indonesia. UNE. pp 191-199.

Matocha, J.E. (1971). Influence of sulfur sources and magnesium on forage yields of coastal bermudagrass (*Cynodon dactylon* (L) Pers). *Agronomy Journal* **63**, 493-496.

McCaskill, M.R., and Blair, G.J. (1987). Particle size and soil texture effects on elemental sulfur oxidation. *Agronomy Journal* **79**, 1079-1083.

McCready, R.G.L., and Krouse, H.R. (1982). Sulfur isotope fractionation during the oxidation of elemental sulfur by *Thiobacilli* in a solonetzic soil. *Canadian Journal of Soil Science* **62**, 105-110.

McLaren, R.G., and Swift, R.S. (1977). Changes in soil organic sulphur fractions due to long term cultivation of soils. *Journal of Soil Science* **28**, 445-453.

Mengel, K., and Kirkby, E.A. (1987). *Principles of plant nutrition*. 4th edition. International Potash Institute, Switzerland.

Morris, R.J. (1987). The importance and need for sulphur in crop production in Asia and the Pacific region. *Proceedings of the Symposium on Fertilizer Sulphur Requirements and Sources in Developing Countries of Asia and the Pacific*. Bangkok, 26-30 Jan., 1987. pp 4-11. FADINAP, FAO, The Sulphur Inst., ACIAR.

Mortvedt, J.J., and Kelsoe, J.J. (1988). Crop response to fine and granular magnesium fertilisers. *Fertilizer Research* **15**, 155-161.

Moser, U.S., and Olson, R.V. (1953). Sulfur oxidation in four soils as influenced by soil moisture tension and sulfur bacteria. *Soil Science* **76**, 251-257.

Nearpass, D.C., and Clark, F.E. (1960). Availability of sulfur to rice plants in submerged and upland soil. *Soil Science Society of America proceedings* **24**, 385-387.

Nelson, W.L., and Terman, B.L. (1963). Nature, behavior, and use of multi-nutrient (mixed) fertilizers. *In* McVickar, M.H., Bridger, G.L., and Nelson, L.B. (eds.), *Fertilizer Technology and Usage*. Soil Sci. Soc. Am., Madison, WI. pp 379-428.

Neptune, A.M.L., Tabatabai, M.A., and Hanway, J.J. (1975). Sulfur fractions and carbon-nitrogen-phosphorus-sulfur relationships in some Brazilian and Iowa soils. *Soil Science Society of America Proceedings* **39**, 51-55.

Nevell, W., and Wainright, M. (1987). Influence of soil moisture on sulphur oxidation in brown earth soils exposed to atmospheric pollution. *Biology and Fertility of Soils* **5**, 209-214.

Noellemeyer, E.J., Bettany, J.R., and Henry, J.L. (1981). Sources of sulfur for rapeseed. *Canadian Journal of Soil Science* **61**. 465-467.

Nõmmik, H. (1966). Particle-size effect on the rate of nitrification of nitrogen fertiliser materials, with special reference to ammonium-fixing soils. *Plant and Soil* **24**, 181-200.

Nor, Y.M., and Tabatabai, M.A. (1977). Oxidation of elemental sulfur in soils. *Soil Science Society of America Journal* **41**, 736-741.

O'Leary, M.J., and Rehm, G.W. (1991). Evaluation of some soil and plant analysis procedures as predicators of the need for sulfur for corn production. *Communications in Soil Science and Plant Analysis* **22**, 87-98.

Olson, R.A., and Rehm, G.W. (1986). Sulfur in precipitation and irrigation waters and its effect on plant growth. *In* Khasawneh, F.E., Sample, E.C., and Kamprath, E.J. (eds.), *The Role of Phosphate in Agriculture*. ASA, CSSA, SSSA., Madison, Wisconsin, USA. pp 559-589.

Osiname, O.A., and Kang, B.T. (1975). Response of rice to sulphur application under upland conditions. *Communications in Soil Science and Plant Analysis* **6**, 585-598.

Owens, L., Lawton, K., Robertson, L.S., and Apostolakis, C. (1955). Laboratory, greenhouse, and field studies with mixed fertilisers varying in water-soluble phosphorus content and particle size. *Soil Science Society of America Proceedings* **19**, 315-319.

Parker, C.D., and Prisk, J. (1953). The oxidation of inorganic compounds of sulphur by various sulphur bacteria. *Journal of General Microbiology* **8**, 344-364.

Phillips, A.B., and Webb, J.R. (1971). Production, marketing, and use of phosphorus fertilizers. *In* Olson, R.A., Army, T.J., Hanway, J.J., and Kilmer, V.J. (eds.), *Fertilizer Technology and Use. 2nd edition*. Soil Sci. Soc. Am., Madison, WI. pp 271-301.

Ponnamperuma, F.N. (1965). Dynamic aspect of flooded soils and the nutrient of the rice plant. *In* 'The Mineral Nutrition of the Rice Plant'. pp 295-328, John Hopkins Press, Baltimore, Maryland.

Prasad, M., and Prasad, R. (1981). Yield and nitrogen uptake by rice as affected by variety, method of planting and new nitrogen fertilisers. *Fertilizer Research* **1**, 207-213.

Prins, W.H., and Rauw, G.J.G. (1989). Use of large granular urea (LGU) to improve efficiency of broadcast urea in wetland rice cultivation. *Fertilizer Research* **19**, 21-27.

Probert, M.E., and Samosir, S.S.R. (1983). Sulfur in non-flooded tropical soils. *In* Blair, G.J., and Till, A.R. (eds.), *Sulfur in South East Asian and South Pacific Agriculture.* Indonesia. UNE. pp 15-27.

Rajan, S.S.S. (1982). Influence of phosphate rock reactivity and granule size on the effectiveness of 'biosuper'. *Fertilizer Research* **3**, 3-12.

Randall, P.J., Spencer, K., and Freney, J.R. (1981). Sulfur and nitrogen fertilizer effects on wheat. I Concentrations of sulfur and nitrogen and the nitrogen to sulfur ratio in grain, in relation to the yield response. *Australian Journal of Agricultural Research* **32**, 203-212.

Rendig, V.V., and McComb, E.A. (1961). Effect of nutritional stress on plant composition: II. Changes in sugar and amide nitrogen content of normal and sulfur-deficient alfalfa during growth. *Plant and Soil* **14**, 176-186.

Rhue, R.D., and Kamprath, E.J. (1973). Leaching losses of sulfur during winter months when applied as gypsum, elemental S or prilled S. *Agronomy Journal* **65**, 603-605.

Robinson, E., and Robbins, R.C. (1968). *Sources, abundance and fate of gaseous atmospheric pollutants.* Prepared for API (Stanford Res. Inst.). Cited by Evans, L.T. (1975).

Rothbaum, H.P., Sewell, J.R., and Evason, W (1980). Water-degradable sulphur/anhydrite pellets for fertiliser use. *New Zealand Journal of Science* **23**, 371-382.

Russell, E.W. (1973). *Soil Conditions and Plant Growth.* 10th edition. Longman Group Limited, London.

Sachdev, M.S., and Chhabra, P. (1974). Transformation of S^{35}-labelled sulphate in aerobic and flooded conditions. *Plant and Soil* **41**, 335-341.

Saggar, S., Bettany, J.R., and Stewart, J.W.B. (1981). Sulfur transformations in relation to carbon and nitrogen in incubated soils. *Soil Biology and Biochemistry* **13**, 499-511.

Samosir, S.S.R. (1981). Some aspects of the sulfur nutrition of rice. M.Sc.Agric. Thesis. University of New England. Armidale.

Samosir, S., and Blair, G.J. (1983). Sulfur nutrition of rice. III. A comparison of fertilizer sources for flooded rice. *Agronomy Journal* **75**, 203-206.

Sander, D.H., and Eghball, B. (1988). Effect of fertiliser phosphorus particle size on phosphorus fertiliser efficiency. *Soil Science Society of America Proceedings* **52**, 868-873.

Santoso, D., Lefroy, R.D.B., and Blair, G.J. (1995). Sulfur and phosphorus dynamics in an acid soil/crop system. *Australian Journal of Soil Research* **33**, 113-124.

Scott, N.M., and Anderson, G. (1976). Organic sulphur fractions in Scottish soils. *Journal of the Science of Food and Agriculture* **27**, 358-366.

Shedley, C.D. (1982). An evaluation of elemental sulfur as a pasture fertiliser. Ph.D Thesis, University of New England, Armidale.

Shedley, C.D., Till, A.R., and Blair, G.J. (1979). A radiotracer technique for studying the nutrient release from different fertiliser materials and its uptake by plants. *Communications in Soil Science and Plant Analysis* **10**, 737-745.

Sholeh (1995). Sulfur and phosphorus effects on elemental S oxidation and the availability of S to corn. Ph.D Thesis. University of New England, Armidale.

Sholeh, Lefroy, R.D.B., and Blair, G.J. (1997). Effect of nutrients and elemental sulfur particle size on elemental sulfur oxidation and the growth of *Thiobacillus thiooxidans*. *Australian Journal of Agricultural Research* **48**, 497-501.

Simon, R.H., and Schollenberger, C.J. (1925). The rate of oxidation of different forms of elemental sulfur. *Soil Science* **20**, 443-449.

Skiba, U., and Wainwright, M. (1984). Oxidation of elemental-S in coastal-dune sands and soils. *Plant and Soil* **77**, 87-95.

Solberg, E.D., and Nyborg, M. (1983). Comparison of sulphate and elemental sulphur fertilisers. *In* More, A.I. (ed), *Proceedings of the International Sulphur-82 Conference.* **2**: 843-852. The British Sulphur Corporation Limited. London.

Starkey, R.L. (1925a). Concerning the physiology of *Thiobacillus thiooxidans*, an autotrophic bacterium oxidizing sulfur under acid conditions. *Journal of Bacteriology* **10**, 135-163.

Starkey, R.L. (1925b). Concerning the carbon and nitrogen nutrition of *Thiobacillus thiooxidans*, an autotrophic bacterium oxidizing sulfur under acid conditions. *Journal of Bacteriology* **10**, 165-195.

Starkey, R.L. (1966). Oxidation and reduction of sulfur compounds in soils. *Soil Science* **101**, 297-306.

Starostka, R.W., Caro, J.H., and Hill, W.L. (1954). Availability of phosphorus in granulated fertilisers. *Soil Science Society of America Proceedings* **18**, 67-71.

Stewart, B.A., and Porter, L.K. (1969). Nitrogen-sulfur relationships in wheat (*Triticum aestivum* L.), corn (*Zea mays*), and beans (*Phaseolus vulgaris*). *Agronomy Journal* **61**, 267-271.

Stewart, B.A., Porter, L.K., and Viets, F.G. (1966a). Sulfur requirements for decomposition of cellulose and glucose in soil. *Soil Science Society of America Proceedings* **30**, 453-456.

Stewart, B.A., Porter, L.K., and Viets, F.G. (1966b). Effect of sulfur content of straws on rates of decomposition and plant growth. *Soil Science Society of America Proceedings* **30**, 355-358.

Swaby, R.J. (1975). Biosuper-biological superphosphate. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture.* Sydney University Press, Sydney; Australia. pp 213-220.

Swanney, B., Boswell, C.C., Enright, P.D., and Sinclair, A.G. (1988). A comparative field evaluation of some potential sulphur fertiliser materials. *New Zealand Journal of Experimental Agriculture* **16**, 183-192.

Tabatabai, M.A., and Al-Khafaji, A.A. (1980). Comparison of nitrogen and sulfur mineralization in soils. *Soil Science Society of America Journal* **44**, 1000-1006.

Takahashi, S., and Ono, S. (1996). Nitrogen release from polyolefin-coated urea with attention to individual weights. *Nutrient Cycling in Agroecosystems* **46**, 153-156.

Tandon, H.L.S. (1987). Sulphur containing fertilizers. *Proceedings of the Symposium on Fertilizer Sulphur Requirements and Sources in Developing Countries of Asia and the Pacific.* Bangkok, 26-30 Jan., 1987. pp 95-100. FADINAP, FAO, The Sulphur Inst., ACIAR.

Terman, G.L., Allen, S.E., and Giordano, P.M. (1973). Dry matter yield-N and S concentration relationships and ratios in young corn plants. *Agronomy Journal* **65**, 633-636.

Thomas, J., and Prasad, R. (1982). On the nature of mechanisms responsible for the higher efficiency of urea supergranules for rice. *Plant and Soil* **69**, 127-130.

Thomson, J.F., Smith, I.K., and Madison, J.T. (1986). Roles and requirements of sulfur in plant nutrition. *In* Tabatabai, M.A. (ed.). *Sulfur in Agriculture.* Agronomy Monograph No.27, Madison, WI. pp 59-107.

Till, R.A., McArthur, G.S., and Rocks, R.L. (1984). An automated procedure for the simultaneous determination of sulphur and phosphorus and of radioactivity in biological samples. *Proceedings of Sulphur-84*, Alberta, Canada, 3-6 June, pp 649-660. Sulphur Dev. Inst., Canada (SUDIC), Calgary, Canada.

Tisdale, L.S., Nelson, W.L., Beaton, J.D., and Havlin, J.L. (1993). *Soil fertility and fertilizers.* Macmillan Publishing Company, USA.

Trudinger, P.A. (1975). The biogeochemistry of sulphur. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture.* Sydney University Press, Sydney; Australia. pp 11-20.

Vaughn, C.E., Jones, M.B., and Ruckman, J.E. (1979). Effects of sulfur-coated urea on California annual grassland yield and chemical composition. *Agronomy Journal* **71**, 297-300.

Vitolins, M.I., and Swaby, R.J. (1969). Activity of sulphur-oxidizing microorganisms in some Australian soils. *Australian Journal of Soil Research* **7**, 171-183.

Wainwright, M. (1979). Effects of pesticides and N-serve on the oxidation of elemental S in soil. *Plant and Soil* **51**, 205-213.

Wainwright, M. (1984). Sulfur oxidation in soils. *Advances in Agronomy* **37**, 350-392.

Waksman, S.A., and Starkey, R. (1923). On the growth and respiration of sulfur-oxidizing bacteria. *Journal of General Physiology* **5**, 285-310.

Wang, C.H., Liem, T.H., and Mikkelsen, D.S. (1976). Sulfur deficiency-A limiting factor in rice production in the lower Amazon Basin II. Sulfur requirement for rice production. *IRI Bulletin No.48*. IRI Research Institute Inc. New York.

Watkinson, J.H., and Kear, M.J. (1996). Sulfate and mineralizable organic sulfur in pastoral soils of New Zealand. I. A quasi equilibrium between sulfate and mineralizable organic sulfur. *Australian Journal of Soil Research* **34**, 385-403.

Watkinson, J.H., and Lee, A. (1994). Kinetics of field oxidation of elemental sulfur in New Zealand pastoral soils and the effects of soil temperature and moisture. *Fertilizer Research* **37**, 59-68.

Weir, R.G. (1970). Factors affecting the availability of sulphur from sulphur fertilizers. *Proceedings of the XI International Grassland Congress.* April 13-23, Surface Paradise, Queensland, Australia. pp 330-384.

Weir, R.G. (1975). The oxidation of elemental sulphur and sulphides in soil. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture*. Sydney University Press, Sydney; Australia. pp 40-49.

Weir, R.G., Barkus, B., and Atkinson, W.T. 1963). The effect of particle size on the availability of brimstone sulphur to white clover. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 314-318.

Williams, C.H. (1967). Some factors affecting the mineralization of organic sulphur in soils. *Plant and Soil* **26**, 205-223.

Williams, C.H. (1975). The chemical nature of sulphur compounds in soils. *In* McLachlan, K.D. (ed.), *Sulphur in Australasian Agriculture*. Sydney University Press, Sydney; Australia. pp 21-30.

Williams, C.H., and Lipsett, J. (1961). Fertility changes in soils cultivated for wheat in southern New South Wales. *Australian Journal of Agricultural Research* **12**, 612-629.

Wu, J., O'Donnel, A.G., and Syers, J.K. (1993). Microbial growth and sulphur immobilization following the incorporation of plant residues into soil. *Soil Biology and Biochemistry* **25**, 1567-1573.

Yadvinder-Singh, and Beauchamp, E.G. (1988). Response of winter wheat to fall-applied large urea granules with dicyandiamide. *Canadian Journal of Soil Science* **68**, 133-142.

Yadvinder-Singh, Malhi, S.S., Nyborg, M., and Beauchamp, E.G. (1994). Large granules, nests or bands: Methods of increasing efficiency of fall-applied urea for small cereal grains in North America. *Fertilizer Research* **38**, 61-87.

Yosida, S., and Chaudhry, M.R. (1979). Sulfur nutrition of rice. *Soil Science and Plant Nutrition* **25**, 121-134.