

NATIVE SULPHUR MINERALIZATION AND MINERALIZATION RATE UNDER AEROBIC INCUBATION IN RICE-BASED SOILS

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ABSTRACT

Sulphur mineralization is a crucial process controlling the availability of sulphur for plant nutrition; however, mineralization rates are strongly dependent on temperature, incubation period and the initial sulphur status of the soil. The objective of this study was to evaluate native sulphur mineralization under aerobic conditions in two rice varieties namely Kamala and Samba Mahsuri with increasing levels of elemental sulphur (0, 20, 40 and 60 kg S ha⁻¹). The soils were incubated at 25 ± 1 and 45 ± 1 °C for 2, 4, 6 and 8 weeks and sulphur mineralization was determined as an increase in 0.15% CaCl₂ extractable sulphur during incubation. The rate of sulphur mineralization was calculated according to Janzen and Bettany (1987). The study revealed that sulphur mineralization increased with an increase in the incubation period up to 6 weeks and then decreased slightly at 8 weeks. The mineralized sulphur at 25 °C increased from 4.46 µg S g⁻¹ at 2 weeks to 9.58 µg S g⁻¹ at 6 weeks of incubation whereas, at 45 °C, it increased from 12.05 to 25.86 µg S g⁻¹ during the same period. During the entire incubation period, sulphur mineralization was greater at 45 °C (20.84 µg S g⁻¹) compared to 25 °C (7.72 µg S g⁻¹). The control treatment had greater sulphur mineralization over the treatment with added sulphur and sulphur mineralization was greater in Kamala than in Samba Mahsuri. Furthermore, a progressive decrease in sulphur mineralization rate was observed with increasing incubation period from 3.36 to 2.12 µg S cm² d⁻¹ at 25 °C and from 9.09 to 5.74 µg S cm² d⁻¹ at 45 °C.

KEYWORDS: Native sulphur, Sulphur mineralization, Elemental sulphur, Aerobic incubation, Rice, Temperature, CaCl₂ –extractable sulphur

INTRODUCTION

Sulphur (S) is a vital plant nutrient and its presence in soil is controlled by a shifting equilibrium between organic and inorganic forms. A considerable share of soil S is present in organic forms which plants cannot take up directly but which serve as a significant reservoir of potentially mineralizable S. The transformation of organic S into inorganic sulphate-S via microbial activity, generally known as S mineralization is a key route for replenishing plant-available S. The extent and direction of these transformations are governed by soil properties, substrate quality, microbial activity and environmental conditions. Vermeiren *et al.* (2018), applying ³⁵S isotope dilution to contrasting soils showed that soil S turnover is governed by the size and dynamics of labile organic S pools and that mineralization makes a substantial contribution to the supply of plant-available S.

Temperature is among the key environmental factors controlling the microbial processes that drive organic S decomposition and mineralization. Shifts in temperature affect microbial growth, enzyme activity, substrate utilisation and the speed at which organically bound S is converted into inorganic forms. Tanikawa *et al.* (2014) showed that soil organic S transformation can proceed through sequential steps with C-bonded S first converted to ester sulphate-S and then to inorganic sulphate-S. Their incubation study also indicated that the rates of these transformations were affected by temperature and soil chemical properties. This dependence on temperature suggests that shifts in soil thermal conditions can considerably alter both the timing and the magnitude of S release. Consequently, measuring mineralization under varying temperature regimes is essential for understanding temporal S availability and for refining estimates of nutrient supply to crops.

Soil moisture is another key factor as it controls oxygen availability, microbial activity and soil redox conditions and thus affects the balance among S mineralization, immobilization and reduction processes. Under aerobic conditions, microbial oxidation and decomposition of organic matter can encourage the formation of sulphate-S while extended waterlogging creates reducing conditions that favour a different sequence of S transformations. This difference is especially relevant in rice-based systems where soils may shift between aerobic and flooded states depending on crop establishment and water management. Recent research by Tao *et al.* (2025) showed that

waterlogging, straw addition and sulphate application significantly changed organic S, available sulphate and reduced inorganic S pools in paddy soil. The study found that organic S mineralization contributed to higher available sulphate during the early incubation period while reducing conditions together with microbial sulphate and iron reduction drove the formation of reduced inorganic S.

Thus, the interplay of temperature, moisture and incubation duration governs the extent and rate of net S mineralization or immobilization in soil. Recent work indicated that the kinetics of S release matter for matching soil S supply with crop demand. Mahal et al. (2022) found that the timing of plant-available S production was affected by S source and mineralization kinetics, underscoring the value of understanding temporal S availability rather than treating soil S as a static nutrient pool. Nevertheless, knowledge remains relatively scarce regarding how temperature and moisture regimes jointly affect the temporal pattern of native soil S mineralization especially in soils linked to rice production. Therefore, this study was carried out to quantify net native soil S mineralization or immobilisation under various temperature and moisture regimes at successive incubation intervals thus, enhancing understanding of S transformation dynamics and their possible contribution to plant-available S.

MATERIALS AND METHODS

Soil Sampling and Preparation

Surface soil samples (0–15 cm depth) were collected from the experimental field of the Indian Institute of Rice Research (IIRR), Rajendranagar, Hyderabad, Telangana, following harvest of the rice crop. The incubation study was conducted using soil samples representing the experimental treatments comprising two rice varieties, Kamala and Samba Mahsuri; two crop establishment methods, direct-seeded rice (DSR) and transplanted rice (TPR); and four sulphur levels, viz., S₀ (0 kg S ha⁻¹), S₁ (20 kg S ha⁻¹), S₂ (40 kg S ha⁻¹) and S₃ (60 kg S ha⁻¹), applied through elemental sulphur. Thus, the soil samples represented the different combinations of variety, crop establishment method and sulphur level used in the field experiment.

The collected soil samples were thoroughly mixed to obtain representative samples and were air-dried under laboratory conditions. The air-dried samples were gently crushed and passed through a 2 mm sieve to remove coarse materials, plant residues and other extraneous materials. The processed samples were used for subsequent incubation studies and analysis of native soil sulphur transformation.

Incubation Studies

The soil samples representing the different field treatments were subjected to incubation for 2, 4, 6 and 8 weeks under two contrasting moisture regimes, viz., aerobic and anaerobic and at two temperature regimes of 25 ± 1°C and 45 ± 1°C. The incubation experiment was undertaken to quantify the temporal changes in native soil S and to assess net S mineralization under different temperature and moisture conditions.

Aerobic Moisture Regime

For aerobic incubation, 10 g of homogenised soil from each treatment was weighed into a 250 mL conical flask. Deionised water was added in sufficient quantity to maintain the soil moisture at approximately 50% water-holding capacity. The prepared samples were incubated separately at 25 ± 1°C and 45 ± 1°C for 2, 4, 6 and 8 weeks. The samples were maintained under aerobic conditions throughout the incubation period, with periodic aeration to prevent excessive accumulation of carbon dioxide.

At the end of each specified incubation period, the soil samples were removed and dried. A 10 g portion of the dried soil was extracted with 50 mL of 0.15% CaCl₂ solution using a 1:5 soil-to-extractant ratio. The suspension was shaken for 30 minutes and subsequently filtered. The sulphate-S concentration in the extract was determined following the method of Chesnin and Yien (1951). Net mineralization of native soil S was calculated from the increase in 0.15% CaCl₂-extractable S over the initial concentration.

Anaerobic Moisture Regime

For the anaerobic incubation, the same procedure was followed for soil sample preparation. However, the soil samples were flooded with deionised water by maintaining a water layer of approximately 2 cm above the soil surface. The water level was maintained throughout the incubation period by adding deionised water periodically to compensate for water loss. The samples were incubated at 25 ± 1°C and 45 ± 1°C for 2, 4, 6 and 8 weeks.

After completion of each incubation period, the samples were removed and dried. Subsequently, 10 g of dried soil was extracted with 50 mL of 0.15% CaCl₂ and shaken for 30 minutes. The suspension was filtered and the extract was analysed for sulphate-S following Chesnin and Yien (1951). A decrease in 0.15% CaCl₂-extractable S relative to the initial concentration was considered indicative of net S immobilisation whereas an increase was considered as net S mineralization.

Calculation of Net Sulphur Mineralization Rate

The rate of net S mineralization was calculated using the equation proposed by Janzen and Bettany, as follows:

$$K = [1 - (1 - m/m_0)^{1/3}] \times (Z \times D_0)/(2t)$$

Where,

K = rate of net S mineralization (µg S cm⁻² day⁻¹)

m = amount of mineralised S (µg), calculated from the increase in 0.15% CaCl₂-extractable S during incubation

m₀ = initial amount of extractable S (µg) at the beginning of the incubation period

Z = density of sulphur (2.07 × 10⁶ µg cm⁻³)

D₀ = particle diameter at the beginning of incubation (0.075 cm), assuming spherical particles

t = duration of the incubation period (days).

The change in 0.15% CaCl_2 extractable S was calculated for each combination of rice variety $\times$ establishment method $\times$ sulphur level $\times$ temperature regime $\times$ moisture regime $\times$ incubation period. Positive changes in extractable S were interpreted as net mineralization whereas negative changes were considered net immobilisation.

RESULTS AND DISCUSSION

Mineralization of Native S under Aerobic Conditions

Incubating soil samples under aerobic conditions resulted in the gradual mineralization of native soil S across the 2, 4, 6 and 8 week incubation periods. The extent of native S mineralization varied considerably depending upon sulphur treatment, rice variety, incubation period and the interactions thereof. At 25°C, the quantity of native S mineralised increased from 4.46 $\mu\text{g S g}^{-1}$ soil at 2 weeks to 9.58 $\mu\text{g S g}^{-1}$ soil at 6 weeks before decreasing slightly to 9.36 $\mu\text{g S g}^{-1}$ soil at 8 weeks. Across the incubation, Kamala exhibited a higher mean mineralization (8.46 $\mu\text{g S g}^{-1}$) in comparison with Samba Mahsuri (6.98 $\mu\text{g S g}^{-1}$). Amongst sulphur treatments, the control recorded the highest mean mineralization (10.09 $\mu\text{g S g}^{-1}$), followed by 20, 40 and 60 kg S ha^{-1} , with values of 8.13, 6.80 and 5.85 $\mu\text{g S g}^{-1}$, respectively. The significant treatment $\times$ variety $\times$ incubation-period interaction indicates that the pattern of native S mineralization varied depending upon the combination of sulphur treatment, variety and incubation duration.

The gradual increase in mineralised S up to six weeks indicates ongoing microbial transformation of native organic S under aerobic conditions. The gradual decrease observed subsequently at eight weeks can be attributed to depletion of easily mineralisable organic-S substrates and a gradual decrease in the substrate available for microbial degradation. Tanikawa et al. (2014) documented that soil organic S is transformed sequentially through different S fractions before becoming available as inorganic sulphate-S, indicating that mineralization of soil organic S is a dynamic process as opposed to occurring at a constant rate. Vermeiren et al. (2018), Gorlapalli et al. (2022), Sahoo et al. (2022) and Kale et al. (2020) similarly reported considerable variation in S mineralization among contrasting soils and showed how labile organic-S pools are key to governing the mineralization potential of soil S.

The higher degree of mineralization observed with Kamala compared to Samba Mahsuri suggests variation in the mineralization potential of soil tied to the respective field treatments. As the incubation utilised soil collected following the field experiment, the differences observed reflect the residual effect of the previous variety $\times$ establishment $\times$ sulphur treatments on the soil S pool and its mineralization potential, as opposed to the direct plant activity during incubation. The lower mineralization observed with the increasing elemental-S application can indicate a comparatively greater contribution of native soil S to the extractable pool in the control treatment.

Effect of Temperature on Native S Mineralization

Increasing the incubation temperature from 25 to 45°C markedly enhanced native S mineralization under aerobic conditions. At 45°C, the mean quantity of S mineralised increased from 12.05 $\mu\text{g S g}^{-1}$ soil at 2 weeks to 25.86 $\mu\text{g S g}^{-1}$ soil at 6 weeks followed by a slight decrease to 25.26 $\mu\text{g S g}^{-1}$ soil at 8 weeks. Kamala demonstrated a higher overall mean mineralization (22.84 $\mu\text{g S g}^{-1}$) than Samba Mahsuri (18.84 $\mu\text{g S g}^{-1}$). The control treatment recorded the highest mean mineralization (27.24 $\mu\text{g S g}^{-1}$) while the corresponding values under 20, 40 and 60 kg S ha^{-1} were 21.96, 18.36 and 15.79 $\mu\text{g S g}^{-1}$, respectively.

The marked increase in mineralization observed at 45°C indicates that temperature had a significant effect on transformation of native organic S. Higher temperature can hasten microbial biochemical reactions and the decomposition of susceptible organic substrates, thereby leading to greater release of inorganic S during the early stages of incubation. Nevertheless, the modest reduction observed after six weeks implies that the easily mineralizable S pool may have gradually diminished as incubation progressed. Mahal *et al.* (2022), Srilatha et al. (2019) and Tuli et al. (2022) similarly drew attention to the importance of mineralization kinetics and temporal pattern of S release in governing the availability of soil S.

The response observed in this study further indicates that temperature impacted both the overall quantity of S mineralised and the temporal pattern of mineralization. The considerably higher mineralization observed at 45°C than at 25°C indicates a pronounced temperature dependence of native soil-S transformation under aerobic conditions.

Rate of Native S Mineralization

The calculated rate of native S mineralization exhibited a gradual decrease as the incubation duration increased under both temperature regimes. At 25°C, the mean mineralization rate decreased from 3.36 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$ at 2 weeks to 2.12 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$ at 8 weeks. Throughout the incubation period, Kamala maintained a higher mineralization rate than Samba Mahsuri. The control exhibited the highest overall rate (4.19 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$), followed by the 20, 40 and 60 kg S ha^{-1} treatments at 2.81, 2.15 and 1.70 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$, respectively.

At 45°C, the mineralization rate was markedly higher than that recorded at 25°C. The mean rate decreased from 9.09 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$ at 2 weeks to 5.74 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$ at 8 weeks. For Kamala and Samba Mahsuri, the overall mean rates were 8.13 and 6.52 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$, respectively. The control treatment displayed the highest mean rate (11.32 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$), followed by 20, 40 and 60 kg S ha^{-1} at 7.58, 5.80 and 4.61 $\mu\text{g S cm}^{-2} \text{ day}^{-1}$, respectively. The reduction in mineralization rate as the incubation duration increased, despite continued accumulation of mineralised S, demonstrates that transformation proceeded fastest during the early incubation period and then gradually slowed down. This pattern can be explained by the preferential decomposition of relatively labile

organic-S fractions in the initial phase, followed by slower transformation of relatively resistant S fractions. Tanikawa et al. (2014) noted that soil organic S fractions differ in their transformation rates, which supports the gradual decrease in mineralization rate observed in this study. Vermeiren et al. (2018) further demonstrated that the mineralization of soil S is closely linked to the size and turnover of labile organic-S pools.

Effect of Sulphur Treatment and Rice Variety

Under both temperature regimes, the control treatment consistently showed more native S mineralization than the elemental-S treatments. At 25°C, the mean mineralization decreased from 10.09 $\mu\text{g S g}^{-1}$ soil under control to 5.85 $\mu\text{g S g}^{-1}$ under 60 kg S ha^{-1} whereas at 45°C it fell from 27.24 to 15.79 $\mu\text{g S g}^{-1}$ soil. This trend indicates that the proportion of native soil S mineralised was relatively greater when no external S was applied.

Kamala also consistently recorded a higher native S mineralization than Samba Mahsuri at both temperatures. At 25°C, the overall mean mineralization was 8.46 $\mu\text{g S g}^{-1}$ for Kamala as opposed to 6.98 $\mu\text{g S g}^{-1}$ for Samba Mahsuri while at 45°C the corresponding values were 22.84 and 18.84 $\mu\text{g S g}^{-1}$, respectively. The greater mineralization observed with Kamala indicates differences in the residual soil environment and organic-S pool that developed under the respective field treatments.

CONCLUSION

The incubation study demonstrated that native soil S mineralization was significantly impacted by incubation temperature, duration, sulphur treatment and rice variety. Under aerobic conditions, mineralization increased steadily up to six weeks, then decreased slightly after eight weeks. However, the mineralization rate decreased continuously as incubation duration increased, indicating a greater contribution from easily mineralisable S fractions during the early incubation period.

The increase in temperature from 25 to 45°C markedly accentuated both the amount and rate of native S mineralization, demonstrating the strong effect of temperature on soil S transformation. The control treatment exhibited greater mineralization than the elemental-S treatments while Kamala consistently exhibited higher mineralization than Samba Mahsuri. Overall, the results demonstrate that native soil S is a dynamic nutrient pool whose mineralization potential varies with environmental conditions and incubation duration. These findings offer valuable insights for understanding how native soil S contributes to plant-available S in rice-based production systems and to optimise timing of S supply in accordance with crop demand.

Table 1. Native S mineralized in aerobic moisture regime over different periods of incubation at 25 °C ($\mu\text{g S g}^{-1}$ soil)

Treatment	Variety	2 weeks	4 weeks	6 weeks	8 weeks	Mean	Mean of T
T ₁ – Control (No S)	Kamala	5.41	9.29	12.41	14.05	10.29	10.09
	Samba Mahsuri	5.25	9.00	11.80	13.50	9.89	
T ₂ – Elemental S @ 20 kg S ha ⁻¹	Kamala	5.04	8.82	11.31	11.09	9.06	8.13
	Samba Mahsuri	4.51	7.00	8.80	8.50	7.20	
T ₃ – Elemental S @ 40 kg S ha ⁻¹	Kamala	4.41	7.72	9.70	8.84	7.67	6.80
	Samba Mahsuri	3.83	5.94	7.47	6.50	5.93	
T ₄ – Elemental S @ 60 kg S ha ⁻¹	Kamala	4.04	7.07	8.89	7.25	6.81	5.85
	Samba Mahsuri	3.20	4.96	6.24	5.12	4.88	
Mean	Kamala	4.73	8.22	10.58	10.31	8.46	
	Samba Mahsuri	4.20	6.72	8.58	8.40	6.98	
	Both varieties	4.46	7.48	9.58	9.36	7.72	
Source of variation		SEm±			CD (P = 0.05)		
Treatment (T)		0.06			0.16		
Variety (V)		0.04			0.11		
Incubation period (P)		0.06			0.16		
T × V		0.08			0.23		
T × P		0.11			0.32		
V × P		0.08			0.23		

Treatment	Variety	2 weeks	4 weeks	6 weeks	8 weeks	Mean	Mean of T
T × V × P		0.16			0.45		

Values are means of three replications. Mean of T is the mean of the two varieties over all incubation periods; NS – non-significant at P = 0.05. T₁: control (no S); T₂, T₃ and T₄: elemental S at 20, 40 and 60 kg S ha⁻¹, respectively. CV = 3.60%.

Table 2. Native S mineralized in aerobic moisture regime over different periods of incubation at 45 °C (µg S g⁻¹ soil)

Treatment	Variety	2 weeks	4 weeks	6 weeks	8 weeks	Mean	Mean of T
T ₁ – Control (No S)	Kamala	14.61	25.08	33.51	37.94	27.79	27.24
	Samba Mahsuri	14.18	24.30	31.86	36.45	26.70	
T ₂ – Elemental S @ 20 kg S ha ⁻¹	Kamala	13.61	23.81	30.54	29.94	24.47	21.96
	Samba Mahsuri	12.18	18.90	23.76	22.95	19.45	
T ₃ – Elemental S @ 40 kg S ha ⁻¹	Kamala	11.91	20.84	26.19	23.87	20.70	18.36
	Samba Mahsuri	10.34	16.04	20.17	17.55	16.03	
T ₄ – Elemental S @ 60 kg S ha ⁻¹	Kamala	10.91	19.09	24.00	19.58	18.39	15.79
	Samba Mahsuri	8.64	13.39	16.85	13.82	13.18	
Mean	Kamala	12.76	22.20	28.56	27.83	22.84	
	Samba Mahsuri	11.33	18.16	23.16	22.69	18.84	
	Both varieties	12.05	20.18	25.86	25.26	20.84	
Source of variation		SEm±			CD (P = 0.05)		
Treatment (T)		0.16			0.45		
Variety (V)		0.11			0.31		
Incubation period (P)		0.16			0.45		
T × V		0.22			0.63		
T × P		0.32			0.89		
V × P		0.22			0.63		
T × V × P		0.45			1.26		

Values are means of three replications. Mean of T is the mean of the two varieties over all incubation periods; NS – non-significant at P = 0.05. T₁: control (no S); T₂, T₃ and T₄: elemental S at 20, 40 and 60 kg S ha⁻¹, respectively. CV = 3.70%.

Table 3. Rate of mineralization of organic S by Janzen and Bettany (1987) equation ($\mu\text{g S cm}^{-2} \text{d}^{-1}$) incubated at 25 °C

Treatment	Variety	2 weeks	4 weeks	6 weeks	8 weeks	Mean	Mean of T
T ₁ – Control (No S)	Kamala	5.17	4.53	3.97	3.48	4.29	4.19
	Samba Mahsuri	4.97	4.33	3.77	3.29	4.09	
T ₂ – Elemental S @ 20 kg S ha ⁻¹	Kamala	3.94	3.42	2.98	2.59	3.23	2.81
	Samba Mahsuri	3.12	2.56	2.11	1.73	2.38	
T ₃ – Elemental S @ 40 kg S ha ⁻¹	Kamala	3.08	2.66	2.30	1.99	2.51	2.15
	Samba Mahsuri	2.33	1.92	1.58	1.30	1.78	
T ₄ – Elemental S @ 60 kg S ha ⁻¹	Kamala	2.48	2.14	1.84	1.59	2.01	1.70
	Samba Mahsuri	1.82	1.50	1.24	1.02	1.40	
Mean	Kamala	3.67	3.19	2.77	2.41	3.01	
	Samba Mahsuri	3.06	2.58	2.18	1.83	2.41	
	Both varieties	3.36	2.88	2.47	2.12	2.71	
Source of variation		SEm±			CD (P = 0.05)		
Treatment (T)		0.016			0.046		
Variety (V)		0.011			0.032		
Incubation period (P)		0.016			0.046		
T × V		0.023			0.065		
T × P		0.032			0.092		
V × P		0.023			NS		
T × V × P		0.046			NS		

Values are means of three replications. Mean of T is the mean of the two varieties over all incubation periods; NS – non-significant at P = 0.05. T₁: control (no S); T₂, T₃ and T₄: elemental S at 20, 40 and 60 kg S ha⁻¹, respectively. CV = 2.93%.

Table 4. Rate of mineralization of organic S by Janzen and Bettany (1987) equation ($\mu\text{g S cm}^{-2} \text{d}^{-1}$) incubated at 45 °C

Treatment	Variety	2 weeks	4 weeks	6 weeks	8 weeks	Mean	Mean of T
T ₁ – Control (No S)	Kamala	13.98	12.25	10.73	9.40	11.59	11.32
	Samba Mahsuri	13.42	11.70	10.19	8.88	11.05	
T ₂ – Elemental S @ 20 kg S ha ⁻¹	Kamala	10.65	9.26	8.04	6.99	8.73	7.58
	Samba Mahsuri	8.42	6.92	5.69	4.68	6.43	
T ₃ – Elemental S @ 40 kg S ha ⁻¹	Kamala	8.32	7.19	6.21	5.37	6.77	5.80
	Samba Mahsuri	6.30	5.19	4.28	3.53	4.83	
T ₄ – Elemental S @ 60 kg S ha ⁻¹	Kamala	6.71	5.78	4.98	4.29	5.44	4.61
	Samba Mahsuri	4.92	4.06	3.35	2.76	3.77	
Mean	Kamala	9.92	8.62	7.49	6.51	8.13	

Treatment	Variety	2 weeks	4 weeks	6 weeks	8 weeks	Mean	Mean of T
	Samba	8.26	6.97	5.88	4.96	6.52	
	Mahsuri						
	Both varieties	9.09	7.79	6.68	5.74	7.33	
Source of variation		SEm±		CD (P = 0.05)			
Treatment (T)		0.06		0.17			
Variety (V)		0.04		0.12			
Incubation period (P)		0.06		0.17			
T × V		0.08		0.23			
T × P		0.12		0.33			
V × P		0.08		NS			
T × V × P		0.17		NS			

Values are means of three replications. Mean of T is the mean of the two varieties over all incubation periods; NS – non-significant at P = 0.05. T₁: control (no S); T₂, T₃ and T₄: elemental S at 20, 40 and 60 kg S ha⁻¹, respectively. CV = 3.91%.

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