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## Responses of Sulfur Metabolism in Plants to Atmospheric Hydrogen Sulfide \*)

By

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### Summary

DE KOK Luit J. 1989. Responses of sulfur metabolism in plants to atmospheric hydrogen sulfide. – *Phyton (Austria)* 29 (2): 189–201. – English with German summary.

H<sub>2</sub>S is a phytotoxic gas, which can affect plant growth at relatively low levels ( $\geq 0.1 \mu\text{l l}^{-1}$ ). Atmospheric H<sub>2</sub>S was rapidly taken up by plant shoots. H<sub>2</sub>S exposure resulted in a rapid accumulation of water-soluble non-protein sulfhydryl compounds in the shoots. In spinach shoots this accumulation was due to enhanced levels of cysteine and glutathione (in darkness also to  $\tau$ -glutamyl-cysteine). The physiological consequences of enhanced levels of sulfhydryl compounds, and its relation to the phytotoxicity of H<sub>2</sub>S are discussed.

### Zusammenfassung

DE KOK Luit J. 1989. Wirkungen von atmosphärischem Schwefelwasserstoff auf den Schwefelstoffwechsel in Pflanzen. – *Phyton (Austria)* 29 (2): 189–201. – Englisch mit deutscher Zusammenfassung.

H<sub>2</sub>S ist ein Gas, das in relativ geringen Konzentrationen das pflanzliche Wachstum beeinflussen kann. Atmosphärisches H<sub>2</sub>S wird von Pflanzensprossen sehr rasch aufgenommen, es bewirkt eine rapide Anhäufung wasserlöslicher, nicht-protein-gebundener Sulfhydrylverbindungen in den Sprossen. In Spinatpflanzen beruht die Akkumulation auf vermehrtem Cystein und Glutathion (im Dunkeln auch auf  $\tau$ -Glutamyl-Cystein). Die physiologischen Folgen des erhöhten Gehalts an Sulfhydrylverbindungen und die Beziehungen zur Toxizität von H<sub>2</sub>S werden diskutiert.

\*) Lecture held on the FESPP meeting Split September 9, 1988.

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## Introduction

H<sub>2</sub>S is a major component in the global sulfur cycle. Natural sources of H<sub>2</sub>S are anaerobic decomposition of sulfur-containing organic matter, volcanic activity and sulfur springs. However, there is also a variety of H<sub>2</sub>S emissions due to industrial activities, which may be the cause of local high levels of H<sub>2</sub>S in the ambient air. Examples are deposits from the utilization of coal, petroleum, natural gas, and emission due to water pollution by organic sulfur compounds. E.g. in the southeastern part of the province of Groningen, The Netherlands, the atmosphere is locally polluted with high levels of H<sub>2</sub>S (peak levels higher than 1  $\mu\text{l l}^{-1}$ ). Here the pollution of the canals with organic material drained off from farina factories, is the source of H<sub>2</sub>S (DE KOK & al. 1985).

H<sub>2</sub>S is a phytotoxic gas which may reduce plant growth at relatively low levels ( $\geq 0.1 \mu\text{l l}^{-1}$ , THOMPSON & KATS 1978, KRAUSE 1979, DE KOK & al. 1983 b, MAAS & al. 1985, MAAS & al. 1987 c). Besides growth reduction, atmospheric H<sub>2</sub>S levels higher than 0.3  $\mu\text{l l}^{-1}$  may cause leaf lesions and defoliation (OLIVA & STEUBING 1976, STEUBING & JÄGER 1978, THOMPSON & KATS 1978). However, low levels of H<sub>2</sub>S ( $\leq 0.1 \mu\text{l l}^{-1}$ ) may stimulate plant growth (THOMPSON & KATS 1978, DE KOK & al. 1983 b). The physiological and biochemical basis for the observed effects of H<sub>2</sub>S on plants is largely unknown.

The present paper reviews and presents new data on the response of sulfur metabolism of plants with have to cope with H<sub>2</sub>S in the atmosphere, and discusses the relation between a disturbed regulation of sulfur assimilation by H<sub>2</sub>S and the phytotoxicity of this air pollutant.

## H<sub>2</sub>S uptake by plants

Atmospheric H<sub>2</sub>S was rapidly taken up by plants and could be used a sulfur source (FALLER 1972, BRUNOLD & ERISMANN 1974, 1975). COPE & SPEDDING 1982 and TAYLOR & al. 1983 observed high H<sub>2</sub>S fluxes into the leaves upon short-term exposure (30 and 240 min) to low atmospheric H<sub>2</sub>S levels (0.04 and 0.12  $\mu\text{l l}^{-1}$ ). The leaf conductance for H<sub>2</sub>S influx depended on the metabolic activity and only at a high metabolic activity it was close to stomatal conductance (COPE & SPEDDING 1982). DE KOK & al. 1989 observed that the H<sub>2</sub>S flux to shoots was almost linear with concentration up to around 0.3  $\mu\text{l l}^{-1}$  H<sub>2</sub>S; at higher concentrations it reached a maximum. The H<sub>2</sub>S flux to shoots proceeded predominantly via the stomata and was rather constant up to 4 days of exposure to both 0.2 and 0.8  $\mu\text{l l}^{-1}$  H<sub>2</sub>S. Up to an atmospheric H<sub>2</sub>S concentration about 0.3  $\mu\text{l l}^{-1}$ , the shoot conductance for H<sub>2</sub>S influx of various species varied between 60 to 90% of the H<sub>2</sub>S influx predicted from shoot conductance for aqueous vapor efflux (stomatal conductance). It was proposed that a rapid incorporation of H<sub>2</sub>S into com-

pounds of the assimilatory sulfur pathway was responsible for the high H<sub>2</sub>S absorption by the plants (COPE & SPEDDING 1982, DE KOK & al. 1989).

#### Accumulation of sulfur compounds upon H<sub>2</sub>S exposure

In general, prolonged exposure of plants to H<sub>2</sub>S resulted in an increased sulfur content of the leaves (BRUNOLD & ERISMANN 1974, STEUBING & JÄGER 1978, THOMPSON & KATS 1978). Long-term exposure of *Spinacia oleracea* L. and *Beta vulgaris* L. to 0.03, 0.1 and 0.3 µl l<sup>-1</sup> H<sub>2</sub>S resulted in an increase in water-soluble sulfhydryl compounds of the shoots (DE KOK & al. 1986). The level of accumulation depended on the H<sub>2</sub>S concentration. Although ageing of the plants caused a decrease of the actual sulfhydryl content of the shoots, the H<sub>2</sub>S induced increase in sulfhydryl content was observed during the entire 6 weeks exposure period. A similar H<sub>2</sub>S induced accumulation was observed in shoots of *Zea mays* L. after two weeks of exposure (DE KOK & al. 1983b).

Short-term exposure of spinach to H<sub>2</sub>S resulted in a rapid accumulation of water-soluble non-protein sulfhydryl compounds in spinach shoots (DE KOK & al. 1985, MAAS & al. 1987; Table 1). Only prolonged H<sub>2</sub>S fumigation (longer than two days) resulted in substantially enhanced sulfate levels in the shoots (MAAS & al. 1985, 1987a, c, Table 1). Already after one hour of exposure of spinach to 0.25 µl l<sup>-1</sup> H<sub>2</sub>S, a significant increase in sulfhydryl content was noticed. In general, at this concentration maximum accumulation, up to 3- to 4-fold of that in control plants, was observed after

Table 1.

Effect of H<sub>2</sub>S on the levels of water-soluble non-protein sulfhydryl compounds and sulfate in spinach shoots. Plants were exposed to H<sub>2</sub>S according to DE KOK & al. 1986b and sulfhydryl and sulfate contents were determined as described by MAAS & al. 1987a.

	Initial value	Exposure 2 days	4 days
SH content			
(µmol g <sup>-1</sup> f. wt.) <sup>1)</sup>			
0 µl l <sup>-1</sup> H <sub>2</sub> S	0.30 ± 0.02	0.27 ± 0.03	0.25 ± 0.03
0.25 µl l <sup>-1</sup> H <sub>2</sub> S	—	0.75 ± 0.12	0.92 ± 0.12
Sulfate content			
(µmol g <sup>-1</sup> f. wt.) <sup>1)</sup>			
0 µl l <sup>-1</sup> H <sub>2</sub> S	3.77 ± 0.30	3.35 ± 0.37	3.19 ± 0.17
0.25 µl l <sup>-1</sup> H <sub>2</sub> S	—	4.18 ± 0.42	5.64 ± 0.25

<sup>1)</sup> Means of 3 measurements with 3 shoots each.

24 h of exposure (DE KOK & al. 1985, MAAS & al. 1987a). Even exposure of spinach in the dark, under conditions where the stomata were not closed, a H<sub>2</sub>S-induced increase in sulfhydryl content of the shoots could be noticed (DE KOK & al. 1985).

The level of sulfhydryl accumulation in shoots depended on the H<sub>2</sub>S concentration and for spinach it was maximum at 1  $\mu\text{l l}^{-1}$  (5-fold of that of untreated plants) after 24 h of exposure (MAAS & al. 1987b). H<sub>2</sub>S-induced sulfhydryl accumulation was also affected by temperature during the exposure (MAAS & al. 1987a, b), e.g. at 15°C the sulfhydryl level was 1.6-fold higher than that at 25°C after 48 h of exposure to 0.25  $\mu\text{l l}^{-1}$  H<sub>2</sub>S (MAAS & al. 1987). However, the light intensity during the H<sub>2</sub>S exposure did not affect the level of sulfhydryl accumulation (DE KOK & al. 1985, MAAS & al. 1987b).

Sulfhydryl accumulation in spinach shoots upon H<sub>2</sub>S exposure was due to enhanced levels of cysteine and glutathione (GSH; DE KOK & al. 1988, BUWALDA & al. 1988, Table 2). However, upon dark exposure also substantial quantities of  $\gamma$ -glutamyl-cysteine accumulated (BUWALDA & al. 1988). A comparison of the response of the different leaves of spinach demonstrated, that young leaves were characterized by a high sulfhydryl content (Table 2). After a 24 h exposure to 0.25  $\mu\text{l l}^{-1}$  H<sub>2</sub>S, young leaves also accumulated higher levels of sulfhydryl compounds than older leaves. However, relative accumulation expressed as ratio of sulfhydryl content of H<sub>2</sub>S exposed leaves to untreated leaves was constant for leaves of different age (around 3.4). Differences in sulfhydryl content between leaves could be only partially explained by differences in dry matter content and were more likely an illustration of the metabolic activity of the tissue. Young leaves were also characterized by a high amino acid content. The amino acid content was not affected after a 24 h exposure to 0.25  $\mu\text{l l}^{-1}$  H<sub>2</sub>S. In light GSH was the major sulfhydryl compound present in untreated spinach leaf tissue (BUWALDA & al. 1988, DE KOK & al. 1988). In untreated spinach plants, the cysteine content accounted for only 12% or less of the water-soluble non-protein sulfhydryl compounds (BUWALDA & al. 1988, DE KOK & al. 1988; Table 2). However, after a 24 h exposure to 0.25  $\mu\text{l l}^{-1}$  H<sub>2</sub>S, the cysteine content could account for up to 50% of the sulfhydryl compounds (DE KOK & al. 1988, BUWALDA & al. 1988; Table 2.). In both young and older spinach leaves there was a more than 10-fold increase in the cysteine content of upon H<sub>2</sub>S exposure (Table 2). In older leaves cysteine was the major sulfhydryl compound which accumulated after a 24 h H<sub>2</sub>S exposure (65% of the accumulated sulfhydryl compounds), however, in young leaves this was GSH (67% of the accumulated sulfhydryl compounds; GSH content was calculated by subtracting the cysteine content from the total sulfhydryl content; Table 2).

Oxidized glutathione level was rather low in spinach shoots (about 0.03  $\mu\text{mol g fresh weight}^{-1}$ ) and its content was only increased 2-fold after a 48 h of exposure to 0.25  $\mu\text{l l}^{-1}$  (DE KOK & al. 1986a). The glutathione

reductase activity was not substantially affected by H<sub>2</sub>S exposure (DE KOK & al. 1986 a).

Short-term H<sub>2</sub>S exposure did not affect the water-soluble protein sulfhydryl content (DE KOK & al. 1985).

When the H<sub>2</sub>S exposure was ceased, the accumulated sulfhydryl compounds in spinach shoots disappeared rapidly (DE KOK & al. 1985, 1986 a, MAAS & al. 1987 b). The major fraction of the accumulated sulfhydryl compounds had disappeared within 48 h after the termination of the H<sub>2</sub>S pre-exposure. The rate of decrease was not significantly affected by temperature (15, 20 and 25°C), photo fluence rate (60 and 170 µmol m<sup>-2</sup> s<sup>-1</sup>)

Table 2.

Effect of H<sub>2</sub>S on the levels of water-soluble non-protein sulfhydryl compounds and amino acids in leaves of 26 days old spinach plants. Plants were exposed in continuous light for 24 hours under conditions as described by DE KOK & al. 1988. Sulfhydryl groups were determined according to DE KOK & al. 1988 and amino acids as described by STUIVER & al. 1988.

		Leaves			
		1 <sup>st</sup> pair	2 <sup>nd</sup> pair	3 <sup>th</sup> pair	Combined
Fresh weight <sup>1)</sup>	(g)	1.54 ± 0.40	2.18 ± 0.51	0.93 ± 0.35	4.69 ± 0.49
Dry matter content <sup>2)</sup>	(%)	7.1 ± 0.1	9.8 ± 0.6	13.1 ± 0.5	9.6 ± 0.4
Amino acid content <sup>2)</sup>					
(µmol g <sup>-1</sup> f. wt.) <sup>2)</sup>					
	0 µl l <sup>-1</sup> H <sub>2</sub> S	2.8 ± 0.2	7.1 ± 1.0	9.8 ± 0.5	6.1 ± 0.3
	0.25 µl l <sup>-1</sup> H <sub>2</sub> S	2.7 ± 0.3	6.9 ± 0.1	10.8 ± 0.2	5.8 ± 0.0
SH content					
(µmol g <sup>-1</sup> f. wt.) <sup>2)</sup>					
	0 µl l <sup>-1</sup> H <sub>2</sub> S	0.17 ± 0.01	0.33 ± 0.04	0.46 ± 0.01	0.31 ± 0.01
	0.25 µl l <sup>-1</sup> H <sub>2</sub> S	0.60 ± 0.04	1.13 ± 0.14	1.58 ± 0.14	1.02 ± 0.07
Cysteine content					
(µmol g <sup>-1</sup> f. wt.) <sup>2)</sup>					
	0 µl l <sup>-1</sup> H <sub>2</sub> S	0.02 ± 0.00	0.04 ± 0.01	0.03 ± 0.02	0.03 ± 0.00
	0.25 µl l <sup>-1</sup> H <sub>2</sub> S	0.30 ± 0.02	0.45 ± 0.07	0.40 ± 0.01	0.40 ± 0.04
Calculated GSH content					
(µmol g <sup>-1</sup> f. wt.) <sup>2)</sup>					
	0 µl l <sup>-1</sup> H <sub>2</sub> S	0.15 ± 0.01	0.29 ± 0.04	0.43 ± 0.03	0.28 ± 0.01
	0.25 µl l <sup>-1</sup> H <sub>2</sub> S	0.30 ± 0.02	0.66 ± 0.06	1.18 ± 0.14	0.63 ± 0.03

<sup>1)</sup> Means of 18 measurements;

<sup>2)</sup> means of 3 measurements with 3 shoots each.

or  $\text{H}_2\text{S}$  concentration (0.25 and  $0.5 \mu\text{l l}^{-1}$ , MAAS & al. 1987b). There was no increase in the oxidized glutathione content in spinach shoots (it even decreased), and no detectable emission of  $\text{H}_2\text{S}$  by shoots was noticed after the  $\text{H}_2\text{S}$  exposure was terminated (DE KOK & al. 1986a). The latter indicated that desulfhydration of cysteine was not significantly involved in the decrease of sulfhydryl compounds. It was suggested that the excessive sulfhydryl compounds (cysteine and GSH) were rapidly metabolized and used e.g. for protein synthesis (DE KOK & al. 1986).

In order to obtain insight into the regulatory aspects of  $\text{H}_2\text{S}$ -induced sulfhydryl accumulation spinach leaf discs were simultaneously exposed to atmospheric  $\text{H}_2\text{S}$  and incubated with sulfate (liquid phase) or to  $\text{H}_2\text{S}$  and inhibitors of sulfate reduction and GSH synthesis (Table 3). Exposure of spinach leaf discs to  $\text{H}_2\text{S}$  in light resulted in comparable strongly increased levels of sulfhydryl compounds than that observed in intact leaves. After a 24 h exposure to  $0.5 \mu\text{l l}^{-1}$   $\text{H}_2\text{S}$  there was a twelve-fold and two-fold increase in cysteine and GSH content, respectively.

Incubation of spinach leaf discs with high concentrations of  $\text{Na}_2\text{SO}_4$  resulted in an increased de novo reduction of sulfate and its subsequent incorporation into sulfhydryl compounds (DE KOK & al. 1981, 1988, DE KOK & KUIPER 1986; Table 3). A 24 hour incubation of spinach leaf discs with 25 mM  $\text{Na}_2\text{SO}_4$  (at this concentration sulfhydryl accumulation was maximum) in the light resulted in a about six-fold increase in the cysteine and two-fold increase in the GSH content (Table 3). A combined exposure of leaf discs to  $\text{Na}_2\text{SO}_4$  and  $\text{H}_2\text{S}$  demonstrated, that the  $\text{H}_2\text{S}$ - and the sulfate-induced sulfhydryl accumulation were not additional; it was intermediate. This indicated, that the sulfide produced by sulfate reduction and the atmospheric sulfide absorbed by the leaf discs competed for the same substrates utilized for the synthesis of cysteine and GSH. The observation that also the cysteine accumulation was intermediate (nine-fold) indicated that  $\text{H}_2\text{S}$ - and sulfate-induced sulfhydryl accumulation occurred simultaneously.

Incubation of spinach leaf discs with 0.25 mM selenate, an inhibitor of sulfate reduction (DE KOK & KUIPER 1986), resulted in a substantial decrease in the GSH content, however, the cysteine content was not affected (Table 3). Higher concentrations of selenate even strongly decreased sulfhydryl content, but also resulted in visible injury of the leaf discs. The observed selenate-induced decrease in GSH content indicated a rapid turnover of GSH in the light. Apparently under conditions where sulfate reduction is reduced, GSH may be utilized as sulfur source. Incubation of spinach leaf discs with selenate reduced strongly both  $\text{H}_2\text{S}$ -induced cysteine and GSH accumulation (Table 3). This may indicate that due to inhibition of sulfate reduction by selenate, part of the absorbed atmospheric  $\text{H}_2\text{S}$  was directly utilized for synthesis of other sulfur containing compounds e.g. proteins.

Incubation of spinach leaf discs with 1 mM buthionine sulfoximine (BSO), a selective inhibitor of  $\tau$ -glutamyl-cysteine synthetase (MEISTER 1983), slightly reduced sulfhydryl compound content, however, resulted in a strong decrease in GSH content, which was replaced by cysteine (Table 3). After BSO incubation the cysteine content accounted for 76% of the sulfhydryl compounds. The observed decrease of GSH content in presence of BSO again demonstrated a rapid in situ turnover of this sulfhydryl compound in the light. In addition, the observed high levels of cysteine in spinach leaf discs after incubation with BSO, demonstrated that its intracellular level was not controlled by feedback inhibition of cysteine synthetase. BSO only slightly reduced  $H_2S$ -induced accumulation of sulfhydryl compounds (Table 3). Also here cysteine was the major sulfhydryl compound present in the leaf discs (71%). In comparison with untreated spinach leaf discs, the GSH content was unaltered by a combined exposure to BSO and  $H_2S$ . This may indicate that GSH was not rapidly metabolized under conditions where cysteine was present in levels which exceed the metabolic needs for reduced sulfur. The observation that  $H_2S$  induced sulfhydryl

Table 3.

Effect of  $H_2S$ ,  $Na_2SO_4$ ,  $Na_2SeO_4$  and buthionine sulfoximine (BSO) on the levels of water soluble non-protein sulfhydryl compounds of spinach leaf discs. Leaf discs were exposed in continuous light for 24 hours. Experimental conditions and determination of the sulfhydryl compounds were according to DE KOK & al. 1988.

	Untreated <sup>1)</sup>	Treatment		
		$Na_2SO_4$ <sup>2)</sup> (25 mM)	$Na_2SeO_4$ <sup>2)</sup> (0.25 mM)	BSO <sup>2)</sup> (1 mM)
SH content				
(nmol leaf disc <sup>-1</sup> )				
0 $\mu l$ l <sup>-1</sup> $H_2S$	40 ± 4	99 ± 5	19 ± 1	33 ± 1
0.5 $\mu l$ l <sup>-1</sup> $H_2S$	140 ± 13	121 ± 5	80 ± 5	120 ± 4
Cysteine content				
(nmol leaf disc <sup>-1</sup> )				
0 $\mu l$ l <sup>-1</sup> $H_2S$	5 ± 1	29 ± 3	5 ± 1	25 ± 1
0.5 $\mu l$ l <sup>-1</sup> $H_2S$	61 ± 5	45 ± 3	39 ± 4	85 ± 4
Calculated GSH content				
(nmol leaf disc <sup>-1</sup> )				
0 $\mu l$ l <sup>-1</sup> $H_2S$	35 ± 3	70 ± 3	14 ± 1	8 ± 0
0.5 $\mu l$ l <sup>-1</sup> $H_2S$	79 ± 9	75 ± 2	41 ± 0	36 ± 0

<sup>1)</sup> Means of 9 measurements and

<sup>2)</sup> means of 3 measurements with 10 leaf discs each.



accumulation was hardly affected under conditions where synthesis of  $\tau$ -glutamyl-cysteine and thus GSH was inhibited, indicated that metabolization of the absorbed atmospheric  $H_2S$  was not subject to feedback regulation by cysteine or GSH.

### Physiological significance of $H_2S$ -induced sulfhydryl accumulation

The sulfur assimilation in plants is subject to regulation. A feedback control of the sulfate reduction by reduced sulfur compounds, especially on the site of adenosine 5'-phosphosulfate sulfotransferase, was noticed (BRUNOLD & SCHMIDT 1976, 1978, WYSS & BRUNOLD 1980, VON ARB & BRUNOLD 1986, BRUNOLD & al. 1987). DE KOK & KUIPER (1986) proposed that the sulfate concentration at the ATP sulfurylase reaction site may also play an important role in the regulation of sulfur assimilation in the plant. Also the ability of plants to emit volatile sulfur compounds ( $H_2S$ ) by the leaves may play a role in the regulation of sulfur assimilation (RENNENBERG 1982, FILNER & al. 1984).

The observed rapid accumulation of sulfhydryl compounds in the presence of  $H_2S$  indicated a direct entry of the reduced sulfur into cysteine and subsequently into GSH. RENNENBERG 1984 proposed that sulfhydryl compounds accumulate in plants, when the reduced sulfur supply exceeds the metabolic sulfur needs. Exposure of leaf tissue to high sulfate levels (GRILL & al. 1979, RENNENBERG & BERGMANN 1979, DE KOK & al. 1981, DE KOK & KUIPER 1986, BRUNOLD & al. 1987; Table 3) or  $SO_2$  (GRILL & ESTERBAUER 1972, 1973, GRILL & al. 1979, 1980, 1982, CHIMENT & al. 1986, MAAS & al. 1987a, b, c, DE KOK & al. 1988) also resulted in enhanced sulfhydryl levels. In comparison to  $H_2S$ , the level of sulfhydryl accumulation upon  $SO_2$  exposure was much lower at an equal concentration (MAAS & al. 1987a, b, c). However, in contrast with  $H_2S$ ,  $SO_2$  exposure resulted in a more rapid accumulation of sulfate. Here, a substantially increased sulfate content was already noted after 24 h of exposure to  $0.25 \mu l l^{-1}$ . At this concentration the accumulation of sulfate in spinach shoots was almost linear with the duration of fumigation for at least up to 6 days (MAAS & al. 1987b). Similar to  $H_2S$ , the increase in sulfhydryl content upon exposure of spinach leaf tissue to  $SO_2$  or high levels of sulfate, could also be ascribed to enhanced levels of GSH and cysteine (BUWALDA & al. 1988, DE KOK & al. 1988; Table 2).

The occurrence of high levels of both cysteine and GSH (and  $\tau$ -glutamyl-cysteine in darkness) upon  $H_2S$ ,  $SO_2$  or sulfate exposure (BUWALDA & al. 1988, DE KOK & al. 1988; Table 2, 3), and the observation that the specific increase of the cysteine pool by BSO, an inhibitor of GSH synthesis, did not significantly affected the  $H_2S$ -induced sulfhydryl accumulation (Table 3), indicated a poorly controlled intracellular level of

cysteine in plants in the presence of excess sulfur (DE KOK & al. 1988). This is in contrast with that, which had been suggested before (RENNENBERG 1982, 1984, FILNER & al. 1984). Even after prolonged exposure of spinach to  $H_2S$ , high levels of both cysteine and GSH were present. E. g. a two weeks exposure of spinach plants to  $0.4 \mu l l^{-1} H_2S$  resulted in almost thirty-fold and three-fold increase in cysteine and GSH content of the second pair of leaves, respectively (L. J. DE KOK, unpublished results). This demonstrated that upon prolonged exposure to  $H_2S$ , regulation of the intracellular sulfhydryl compounds was not altered in such a way that low cysteine levels were obtained.

From  $H_2S$  flux measurements it was estimated that 25% of the total  $H_2S$  taken up by spinach shoots could be revealed in the water-soluble non-protein sulfhydryl fraction after an exposure to 0.2 or  $0.8 \mu l l^{-1} H_2S$  for 3 days (DE KOK & al. 1989). These data indicated that during the first 24 h of exposure the greater part of the  $H_2S$  taken up by the shoots was incorporated into sulfhydryl compounds, since maximum accumulation of these compounds was reached after this period. In addition, the observation that  $H_2S$  flux to shoots was rather constant up to 4 days of exposure, indicated that the rate of accumulation of sulfhydryl compounds in the shoots was not a reflection of the actual  $H_2S$  uptake by plants (DE KOK & al. 1989). The fate of the remaining fraction of  $H_2S$  taken up by the plant was unclear. Part of the reduced sulfur could be utilized for plant growth (MAAS & al. 1987 c, DE KOK & al. 1989) or may be oxidized and responsible for the observed increased sulfate content upon prolonged  $H_2S$  exposure (MAAS & al. 1985, 1987 a, b, c; Table 1). Whether photosynthetic electron transport is involved in the oxidation of sulfide needs further study (DE KOK & al. 1983 a). At least part of the accumulated reduced sulfur compounds were transported to the roots, since exposure of spinach to  $H_2S$  resulted also in a two-fold increase in GSH content in the roots (from  $2.6$  to  $5.1 \mu mol g$  dry weight $^{-1}$ ) after an exposure to  $0.25 \mu l l^{-1}$  for 2 days (F. BUWALDA & W. VISSER, personal communication). They observed no substantial increase in the cysteine content of the roots upon  $H_2S$  exposure, which supported the suggestion of RENNENBERG & al. (1982, 1984), that GSH is the major transport form of reduced sulfur in the plant.

From the observed high  $H_2S$  fluxes to shoots and the rapid incorporation of  $H_2S$  into cysteine,  $\gamma$ -glutamyl-cysteine and GSH, a direct involvement the sulfur assimilatory pathway in the rapid  $H_2S$  absorption was suggested (DE KOK & al. 1989). They proposed that cysteine synthase played an direct role in fixation of  $H_2S$ .

### Physiological background of the phytotoxicity of $H_2S$

The physiological consequences of enhanced levels of sulfhydryl compounds in plants in the presence of  $H_2S$  are unknown. Evidently, some

species may tolerate high levels of sulfhydryl compounds in the shoots in the presence of  $H_2S$ , without phytotoxic effects (MAAS & al. 1987c). However, the composition of the sulfhydryl pool and the subcellular localization of the accumulated sulfhydryl compounds in the different species needs to be studied. It was proposed that GSH may function as a temporary storage compound of excess sulfur (RENNENBERG 1982, 1984; DE KOK & al. 1986a). However, GRILL & al. 1979, 1980, 1982 suggested that permanent high levels of GSH may alter regulation of cellular metabolism and may result in phytotoxic effects. RENNENBERG 1981 has reported that high intracellular levels of cysteine are toxic to plant cells. DE KOK & al. 1988 observed that *in vitro* cysteine may react with aldehydes. Whether reactions of cysteine with metabolically active aldehydes are involved in its toxicity, and the relation between its accumulation and the phytotoxicity of  $H_2S$  ( $SO_2$ ) needs further investigation.

DE KOK & al. 1989 observed that there was no direct relation between the  $H_2S$  absorption by shoots and the sensitivity of the species to  $H_2S$ . This indicated, that the toxic reaction of  $H_2S$  with cellular constituents, resulting in a reduced growth, was not directly related to the quantity of  $H_2S$  incorporated into the shoots with time. They proposed, that the *in situ* sulfide concentration at the reaction site, or the cellular localization of produced toxic components, or the degree of penetration of sulfide to e. g. the meristems were more important factors in the occurrence of  $H_2S$  induced growth reduction.

Even though photosynthetic processes may be reduced upon  $H_2S$  exposure (TAYLOR & SELVIDGE 1984, MAAS & al. 1988), it has been demonstrated that a direct effect on photosynthesis was not the initial cause of the phytotoxicity of  $H_2S$  for spinach. MAAS & al. 1987a observed equal yield reduction after a 14 days exposure of spinach to  $0.25 \mu l l^{-1} H_2S$ , either only during the 12 h photoperiod or only during the 12 h dark period.

$H_2S$  may also alter amino acid metabolism and nitrogen assimilation in plants (VAN DIJK & al. 1986, DE KOK & al. 1986b). However, it is unclear whether the effects on nitrogen metabolism are involved in the phytotoxicity of  $H_2S$ .

The activity of NADH oxidizing enzymes of spinach shoots was reduced by  $H_2S$  exposure. This reduction was maximum after a two day exposure and then could be related to reduction in relative growth rate by  $H_2S$  (MAAS & DE KOK 1988). The *in vitro* NADH oxidation capacity by shoot extracts showed promise as an early indicator for growth reduction by  $H_2S$ .

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