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9. ABSTRACT

This bibliography lists papers published in specialized journals since 1966. In addition to studies specifically oriented to sulfur, other indirectly related to this subject have been included. Special attention was given to soils of the tropics but papers related to sulfur in soils of the temperate regions were included when considered relevant to the tropics. Titles have been grouped under the following topics: Forms of sulfur in soils: sulfate adsorption by plants; response to sulfur by plants; availability of sulfur in soils; sulfur adsorption by plants; sulfur deficiencies in plants; mobility of sulfur in soils; transformation of sulfur in soils; atmospheric sulfur inputs. About 115 references are annotated.

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A PARTIALLY ANNOTATED BIBLIOGRAPHY ON SULFUR IN SOILS OF THE TROPICS

by

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INTRODUCTION

Sulfur has received attention during the last years as a result of more frequent reports on sulfur deficiencies all over the world. The problem has been detected in the United States, France, Japan, Norway, Sweden, New Zealand, Australia, Central and West Africa, and Central and South America as well as Southeast Asia.

The increasing evidence of the importance of sulfur as a nutrient for plants has prompted national and international meetings. Most of the research work on sulfur has been presented or referred to in these meetings, their proceedings providing excellent source of references.

In addition, Jordan and Ensminger published a comprehensive review on sulfur in soils in Advances in Agronomy, Volume X, (1958) that contained much of the information available at this time.

Later in 1964, the Fifth International Symposium of Agrochemistry held at Palermo, Italy, was devoted to sulfur in agriculture. Important papers presented covered a wide range of aspects related to sulfur and extensive review on the subject have been published in a special volume of "Agrochemica", Pisa, Italy.

In 1966 a Symposium on Sulfur in Agriculture was held at Muscle Shoals, Alabana, organized by the Tennessee Valley Authority and The Sulfur Institute. The papers presented in this event were published in Soil Science, Volume 101, entirely devoted to sulfur.

Finally, in 1970 a similar event occurred at Versailles, France, sponsored by The Sulfur Institute (London) and the French Association for Soil Study. The papers presented have been published in a special issue of Annales Agronomiques, Numero Hors Serie, in 1972, published by the Institut National de la Recherche Agronomique.

These three events represent the most important international meetings on sulfur and probably the most important concentration of papers on this subject. More recently, McLachalan in cooperation with many other workers published a special manual of sulfur in relation to Australian agriculture (K. D. McLachland, ed., "Handbook on Sulfur in Australian Agriculture," CSIRO, Australia, 1974).

In this bibliography are listed papers published in specialized journals from 1966 to this date. An almost complete review of Soils and Fertilizers and Fertilizer Abstracts was made for this period. In addition, the last ten years of Tropical Agriculture, as well as Turrialba, Sols Africains, and Soil Science and Plant Nutrition were reviewed. Selected titles appeared in the following journals were also included: Soil Science, Soil Science Society of America Proceedings, Agronomy Journal, Australian Institute of Agricultural Science Journal, Australian Journal of Soil Research, Journal of Soil Science, New Zealand Journal of Agricultural Science, New Zealand Journal of Experimental Agriculture, Plant and Soils, Soils and Crops, Geoderma, Agrochimica, Oleagineaux, L'Agronomie Tropicale, Tropical Abstracts, Potash and Tropical Agriculture, The Sulfur Institute Journal, Sulfur Institute Technical Bulletin, and New Zealand Journal of Agricultural Science.

Works specifically oriented to studies on sulfur in soil have been considered but others indirectly related with this subject have also been included. Special attention was given to tropical soils but papers related to sulfur in soils of the temperate regions were also included when considered of interest for tropical soils too. Titles have been grouped by topics. Some articles covering several topics of sulfur in soils have been included under the topic most directly related to it according to the abstract.

FORMS OF SULFUR IN SOILS

Bhan, C. and B. R. Tripathi. 1975. The forms and contents of sulfur in some soils of U. P. Soils and Fertilizers 38(1):5.

Organic, total and sulfate sulfur was studied in some alluvial soils of Uttar Pradesh.

Bhardwaj, S. P. and A. N. Pathak. 1969. Fractionation of sulfur in soils of Utai Pradesh and its relation to phosphorus. Soils and Fertilizers 33(6):561.

Average values of organic, water soluble, and sulfate sulfur were 56.6, 45.2 and 9.5 ppm of S. Heating the soil increased the solubility of sulfate sulfur, the duration of heating being more effective than temperature. Mineral, organic, and available phosphorus averaged 90.3, 9.7 and 1.5 percent of total P.

Bhardwaj, S. P. and A. N. Pathak. 1969. Carbon, nitrogen, phosphorus, and sulfur contents on kampur soils. Soils and Fertilizers 34(4):359.

C:N:organic P:organic S were 100:12.5:1.3:1.2. Sulfur fractions were non-SO_4, organic S, total water soluble SO_4-S.

Bromfield, A. R. 1972. Sulfur in northern Nigerian soils. I. Effect of cultivation and fertilizers on total S and sulfate patterns in soil profiles. Journal of Agricultural Science 78(3):465-470.

Organic sulfur decreased with depth and distribution was strongly affected by the root remains of natural fallow. After 19 years root remains disappeared and organic S distribution reflected crop root distribution. Under natural vegetation there was little sulfate sulfur but it accumulated in the subsoil after clearance. Soils have a well-defined sulfate sorption pattern.

Bromfield, A. R. 1972. The effect of cultivation and fertilizers on total S and sulfate patterns in soil profiles. Tropical Soil Research Seminar, University of Ibadan.

Distribution of organic sulfur and sulfate sulfur in soils of the northern Guinea savannah under different conditions of management was studied. Profiles under natural vegetation contained little sulfate sulfur but it accumulated in the subsoil after clearance when sulfur was not removed. Almost all the sulfur applied with fertilizers was in the profiles or removed in harvested crops but losses from erosion and leaching were very small.

Dabin, B. 1972. Preliminary results of a survey of the sulfur content of the soils of tropical Africa. Int. Symp. on Sulfur in Agric., Annales Agron. Numero Hors Serie, 72(1):113-136.

Total sulfur varied from 20 to 300 ppm. The highest amount corresponded to organic hydromorphic, entrophic brown and ferrallitic soils and the lowest in ferruginous soils, mineral hydromorphic sandy soils and Vertisols. Sulfur was mainly organic as indicated by S:C and S:N ratio which were 1:100 and 1:10 respectively.

Goncalvez, M. H. and J. M. Marques. 1972. Available sulfur in some soils of Lourenco Marques. Soils and Fertilizers 37(7):176 (1974). Revista de Ciencias Agronomicas A(5):63-65.

NH_4Ac extractable sulfur ranged from 0.15 to 0.35 mg/100 g of soil in areas of little industrial pollution to 5.00 - 20.25 mg/100 g of soil in highly polluted areas.

Grigor'ev, A. A. and A. S. Fat'yanov. 1973. Some results of the investigation of the sulfur cycle in the Gorkic region. Soils and Fertilizers 36(10):401.

Only 2 to 6 percent of the total sulfur in the plowed layer is mineral sulfur. Removal of sulfur in two-years period was (eight crops) from 5.8 to 13.6 kg/ha of sulfur per year and atmospheric precipitation supplied 9 to 17 kg/ha of sulfur near industrial areas and 4.5 to 8.0 in agricultural regions.

Joshi, D. C., J. S. Choudhari, and S. U. Jain. 1973. Distribution of sulfur fraction in relation to forms of phosphorus in soils of Rajasthan. Soils and Fertilizers 38(6):151.

Forms of sulfur in soils of different texture and rainfall areas were measured.

Kanwar, J. S. and S. Mohan. 1966. Sulfur in soils. Distribution of forms of sulfur in Punjab soils. Soils and Fertilizers 29(1): 26.

Sulfate form predominates in calcareous soils of pH 7 while organic forms abound in acid soils. The C, N, and organic S ratio was 100/11.2/1.34.

Kanwar, J. S. and P. N. Takkar. 1968. Distribution of sulfur forms in tea soils of the Punjab. Soils and Fertilizers 31(2):108.

Soils from higher altitudes (4,000 to 6,000 feet) contained higher amounts of total and organic sulfur than soils from lower altitudes. SO_4-sulfur constituted a small proportion of total S while organic forms dominated with 72 percent.

Schalscha, E. B., C. Estrada, and G. G. Galindo. 1972. Sulfur status of some volcanic ash derived soils in Chile. Soils and Fertilizers 35(6):661.

Low levels of easily soluble sulfur, moderate levels of adsorbed sulfur and substantial amounts of organic sulfur were found in five dystrandepts and two hapludults.

Shudla, V. C., and A. K. Gheyi. 1972. Sulfur status of some Rajasthan soils. Soils and Fertilizers 35(2):122.

Total, organic, and inorganic sulfur contents of Rajasthan soils and relation to sulfur extracted by some reagents was studied.

Tabatabai, M. A. and J. M. Bremner. 1972. Sulfur in Iowa soils. Sulfur Institute Journal 8(1 & 2):10-13.

Inorganic sulfur accounts for 1 to 5 percent of total sulfur in surface soils and occurred entirely as SO_4. Forty-one to seventy-eight percent of organic sulfur was accounted for as ester-sulfate sulfur and carbon-bonded sulfur. Average content of mineralizable sulfur was 0 to 6 ppm incubated at 30°C.

Tabatabai, M. A. and J. M. Bremner. 1972. Distribution of total and available sulfur in selected soils and soil profiles. Agronomy Jour. 64(1):40-44.

Ninety-five to ninety-eight percent of total S in 64 surface soils was organic sulfur. Total sulfur contents ranged from 57 to 618 ppm and sulfate sulfur 1 to 26 ppm. Total sulfur decreased with depth and subsurface samples contained less sulfate sulfur than did surface samples. These soils have low reserves in plant available sulfur.

Trocme, S. 1972. Sulfur contents of European soils. International Sympos. on Sulfur in Agric., Versailles. Annales Agronomiques Numero Hors Serie, 72(1):103-112.

Total sulfur contents range from 100 ppm to 800 ppm. Seventy-five to ninety percent of total sulfur is organic sulfur and variation in sulfur status is linked with variation in organic matter content.

Venkateswarlu, J., B. V. Subbiah and R. V. Tamhane. 1970. Vertical distribution of forms of sulfur in selected rice soils of India. Soils and Fertilizers 33(1):8.

Total and organic sulfur at 0 to 15, 15 to 30, 30 to 46, 46.6 and 61.9 cm depth were studied. Both decreased with depth but SO_4 distribution was inconsistent.

Virmani, S. M. and J. S. Kanwar. 1972. Distribution of forms of sulfur in six profiles of Northeast India. Soils and Fertilizers 35(2):123.

Distribution of sulfur forms in soils profiles was studied. Total and organic sulfur decreased with depth. In arid brown and tropical arid brown soils more than 50 percent of sulfur was nonsulfate sulfur.

SULFATE ADSORPTION BY SOILS

Ahmed, F., M. Karim, and A. Islam. 1968. Study of the isotopic exchange behavior of sulfate in soil as related to equilibrium concentration. Soils and Fertilizers 32(3):229.

All soils except Dulahazara soil gave a negative value for isotopically exchangeable sulfate for a range of equilibrium concentrations ranging from 5 to 60 ppm S for low sulfate fixing soils and 5 to 155 ppm S for high sulfate fixing soils.

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

Adsorption isotherms for sulfate on hematite, pseudoboehmite, and kaolinite showed that for both oxides the isotherms were almost completely irreversible with respect to equilibrium concentration. Kaolinite was instead, completely reversible. While sulfate adsorbed on kaolinite clay is weakly held and easily released, that sorbed on Fe or Al oxides will be highly resistant to leaching and less available to plants.

Barrow, N. J. 1967. Studies on the adsorption of sulfate by soils. Soil Sci. 104:342-349.

Adsorption isotherms were constructed for sulfate adsorption from $CaCl_2$ solutions containing K_2SO_4. Ability to adsorb sulfate was correlated to ability to adsorb phosphate. Partial regression coefficients for extracted Al were significant but not for extracted Fe by citrate-dithionite.

Barrow, N. J., K. Pencer, and W. M. McArthur. 1969. Effects of rainfall and parent material on the ability of soils to adsorb sulfate. Soil Sci. 108:120-126.

The ability of soils to adsorb sulfate was measured by equilibration with $CaCl_2$ solution containing graded concentrations of sulfate. In soils from areas with an annual rainfall of over 30 in/yr the ability to adsorb sulfate increased with increasing rainfall. Soils derived from basic rocks adsorbed more than those derived from acidic rocks.

Barrow, N. J. 1969. Effects of adsorption of sulfate by soils on the amount of sulfate present and its availability to plants. Soil Sci. 108:193-201.

The amount of extractable sulfate in unfertilized soils was highly correlated with the soils' capacity to adsorb sulfate. Rainfall supplying S or causing its leaching affected this relationship in different regions. Soils possessing high adsorption capacities for sulfate show slower rate of absorption by plants than nonadsorbing soils.

Barrow, N. J. 1970. Comparison of the adsorption of molybdate, sulfate and phosphate by soils. Soil Sci. 109:282-288.

Adsorption studies by equilibration with 0.01 M $CaCl_2$ solutions containing increasing amounts of K_2SO_4, Na_2MoO_4, or KH_2PO_4 were performed. Results show that with decreasing pH from 6 to 4 the ratio SO_4/PO_4 adsorbed increased three-fold and that of MoO_4/PO_4 adsorbed increased twenty-fold.

Barrow, N. J. 1972. Influence of solution concentration of calcium on the adsorption of phosphate, sulfate, and molybdate by soils. Soil Sci. 113(3):175-180.

Fertilizer requirements and availability of nutrients are affected by the ability of the soil to adsorb $HPO_4^{=}$, $SO_4^{=}$, and $HMoO_4^{-}$. Three soils with high ability to adsorb anions were shaken with solutions containing variable amounts of these anions and five levels of Ca. Adsorption of anions was measured after 24 hours. The ionic products tended to increase with increasing Ca concentration.

Bayley, J. M. 1974. Changes in the adsorbed sulfate status of a yellow-brown earth after phosphate fertilization and legume growth. New Zeal. Jour. Agric. Res. 17(2):257-265.

Phosphate fertilization on yellow-brown earth produced downward movement of adsorbed sulfate.

Bhardwaj, S. P. and A. N. Pathak. 1970. Effect of hydrogen ion concentration on sulfate retention. Soils and Fertilizers 33(4):343.

The magnitude of sulfate retention followed the order: kaolinite, bentonite, hill soil, rakar soil, parwa soil, alluvial soil, and increased with decreasing pH. Negative fixation at pH 6.0 was observed. The second layer (22.9 to 45.8 cm) adsorbed more sulfate.

Catani, R. A., N. A. Gloria and G. C. Vitti. 1973. Sulfate adsorption by soils. Soils and Fertilizers 36(10):400.

Adsorption of $SO_4^{=}$ by soil samples from the A and B horizons increased with increasing concentrations of $SO_4^{=}$ in the equilibrium solution and decreased with increasing pH.

During, C. and M. Cooper. 1974. Sulfate nutrition and movements in a soil with high sulfate sorption characteristics. New Zeal. Jour. of Exp. Agric. 2(1):45-51.

One hundred sixty-eight kg/ha of S as gypsum was adequate for pasture growth for five years with annual dry matter yields as high as those from four annual applications of 45 kg/ha. With 3000 mm rainfall over ET in five years, applied sulfate did not penetrate below 45 cm.

Fox, R. L., S. M. Hasan, and R. C. Jones. 1971. Phosphate and sulfate sorption by Latosols. Int. Symp. in Soil Fert. Evaluation, New Delhi, 1971. Vol I, 857-864.

Anion sorption reactions are very important in highly weathered soils due to a large component of positive charges at low pH and extensive surfaces low in Si. The intensity of P retention by soils according to their mineralogy was: amorphous hydrated oxides, goethite-gibbsite, kaolinite, 2:1 clays.

Fox, F. L. 1974. Examples of anion and cation adsorption by soils of tropical America. Trop. Agric. 51(2):200-210.

Volcanic ash weathering quickly develop P and S adsorption capability. Sulfate accumulates in large quantities in subsoils of most highly weathered Oxisols and Dystrandepts.

Hague, I., and D. Walmsley. 1973. Adsorption and desorption of sulfate in some soils of the West Indies. Geoderma 9(4):269-278.

Adsorption and desorption of sulfate at different concentration was studied. Adsorption isotherms followed Langmuir equation at low concentration. Desorption was only 32.7 percent and 76.4 percent of initially adsorbed sulfate with four extractions with KH_2PO_4.

Hague, I. and D. Walmsley. 1974. Sulfur investigations in some West Indian soils. Soils and Fertilizers 37(10):287.

Pot experiments with Brassica chinensis show response to added sulfur on all soils. Sulfate adsorption followed the Langmuir equation at low concentration of solution sulfate and was correlated with free Al_2O_3 in soils.

Koter, M., H. Panak, W. Grzesiuk et al. 1966. Studies using S^{35} on sulfate adsorption by some humic soil substances. Soils and Fertilizers 29(2):137.

Peat soils adsorbed much more S than mineral soils did, fulvic and humic acids representing 25.1 and 49.2 percent of total S adsorbed. With increasing acidity of the soil environment the rate of S adsorption increased in fulvic acids and decreased in humic acids.

Koter, M., H. Panak, and T. Wojnowska. 1973. Sorption and desorption of sulfate ions by various soil sorbents. Soils and Fertilizers 36(3):95.

Sorption of sulfate by several materials including Al_2O_3, Fe_2O_3, kaolinite, clayey soil, and low moor peat was studied. Seventy-three to 80 percent of adsorbed sulfate was leached with water from low moor peat, clay, kaolinite, and clayey soil but only 11 to 32 percent from Al_2O_3 and Fe_2O_3.

Toshiyuki, Wakatsuki, H. Furukawa and K. Kawaguchi. 1974. Specific and nonspecific adsorption of inorganic ions. I. Evaluation of specific adsorbability by means of minimum concentration for specific adsorption. Soil Sci. Plant Nutr. 20(4):353-362.

Relative specificities of several inorganic ions based in the MCSA at some pH values on different adsorbants (SiO_2, $Fe(OH)_3$, Al-coated SiO_2) was studied.

RESPONSE TO SULFUR BY PLANTS

Adams, A. F. R. 1974. Sulfur on New Zealand pastures--effect of rates and forms. Soil Fertilizers 37(5):139.

Twenty-two kg/ha of S as gypsum supplies sufficient sulfur to pasture on sandy loam soil. Similar result was obtained with one application of 88 kg/ha of elemental sulfur once for a four-year period.

Arora, S. K. and U. P. Luthra. 1974. Improvement in the quality of Phaseolus aureus Linn. by the application of S, P, and N. Soils and Fertilizers 37(7):198.

Seed protein contents and methionine, cystine and cysteine contents were increased by N, P, and S.

Blakemore, L. C., T. E. Ludecke, M. L. Leamy et al. 1969. A study of the pattern of sulfur responses shown by dryland lucerne on some brown-gray earths. New Zeal. Jour. Agric. Res. 12:333-351.

In trials where no response to S topdressing was observed, sulfate was present at 2 to 4 feet soil depth. Where response occurred no sulfate accumulation was present.

Blue, W. E. 1969. Fertilizer response with Pangola grass on Puletan loamy find sand, British Honduras, indicated by pot experiments. Trop. Agri. 40(1):25-30.

Pot experiments with highly leached soils from the coastal "Pine Ridge" using Pangola grass as indicator plant showed yield increase of 13-fold by adding phosphorus but no response to K, Mg and S was observed.

Braud, M. 1970. Sulfur fertilization of cotton in tropical Africa. Sulfur Institute Jour. 5:3-5.

Sulfur deficiencies were observed in central Africa where sulfur-free fertilizer were used in place of ammonium sulfate. Experiments using varying rates of N and S were evaluated. Suggested N/S ratios (optimum) were given.

Courpron, C., M. Menet, and E. Pelabon. 1973. Fertilizing winter colza on sandy soils of the Gascony heathlands. Soil and Fertilizers 37(2):39.

Yield increased up to 150 percent after application of 50 kg/ha of S to winter colza grown in sandy soils with high ratio C/N and organic matter content.

Das, S. K. and N. P. Datta. 1975. Sulfur fertilization for increased production and grain quality. Soils and Fertilizers 38(1):23.

Protein content of grains and yield increased with sulfur application after five years of continuous use of S-free fertilizer in a paddy-wheat-onion-maize rotation on alluvial sandy clay loam soil.

De Freitas, L. M. M., F. P. Gomes, and W. L. Lott. 1972. Effects of sulfur fertilizer on coffee. Fert. Abstracts, 5(11):297.

Coffee yield increased significantly with applications of 30 to 60 lb of S/acre.

Dungarwal, H. S., P. N. Mathur, and H. G. Singh. 1975. Effect of foliar sprays of sulfuric acid with and without elemental sulfur in the prevention of chlorosis in peanut (Arachis hypogaea L.). Soils and Fertilizers 38(8):272.

Sulfur increased per yield by 137 to 197 percent and increased S leaf content in a calcareous soil of pH 8.4.

Farina, M. P. W., G. W. Gross, and P. Channon. 1974. Influence of sulfur on the yield of a grass-clover pasture fertilized with different sources of phosphorus. Fertilizers Abstracts, 7(8):204.

Annual topdressing of superphosphate produced marked increases of yield compared to rock phosphate. P and S analysis demonstrated that this was due to S of superphosphate. Sulfur requirements were estimated at more than 30 kg/ha/yr.

Halais, P. and A. Girault. 1973. Correction of sulfur deficiency in sugarcane in Madagascar. Soils and Fertilizers 38(8):260.

Application of 48 kg S/ha increased dry matter from 53 to 77 t/ha and extractable sugar from 8.5 to 8.9 percent in soils in which sulfur-free fertilizer were used since 1966.

Hanley, P. K., M. D. Murphy, and T. O'Donnell. 1974. Beneficial effects of sulfur on permanent pastures. Soils and Fertilizers 37(11):356.

From 1971 to 1972, sulfur-free fertilizers were applied annually on Italian ryegrass grown in an entic typorthod soil. In 1973 gypsum was applied and beneficial effects were visible four months later and increase in dry matter was 12 to 15 percent.

Haque, I. and D. Walmsely. 1973. Response of pak-choi (Brassica chinensis L.) to added sulfur in some West Indian soils. Tropical Agriculture 50(1):55-62.

Significant responses to $K_2SO_4^{35}$ or Na_2SO_4 were obtained in all soils but two of low pH in which response was observed only after liming.

Hill, G. D. 1973. Response of white Spanish peanuts to applied sulfur, inoculation and captan spraying in the wet lowlands of New Guinea. Fertilizers Abstracts 6(3):71.

There were highly significant increases in yields of kernels to applied S up to 60 kg/ha as elemental sulfur. Significant increase in nut size was observed with sulfur.

McLachland, K. D. and D. G. DeMarco. 1973. Comparison of fertilizer programs for the development and maintenance of sown pasture on a sulfur deficient basaltic soil. Aust. Jour. Exp. Agric. and Anim. Husbandry 13(60):75-80.

Most efficient use of fertilizer ($CaSO_4$) was made when the requirement of the pasture (33.6 kg S/ha) was fully met in the first year and subsequent annual application of 8.4 kg S/ha.

Nyborg, M., C. F. Bentley, and P. B. Hoyt. 1974. Effect of sulfur deficiency on seed yield of turnip rape. Soils and Fertilizers 37(11):360.

Turnip rape grown for seed is particularly susceptible to sulfur deficiency. An application of 30 kg/ha of S is generally adequate for S deficient soils in Western Canada.

Ollaguier, M. 1973. Anionic nutrition of the oil palm. Application to fertilizer policy in North Sumatra. Oleagineux 28(1):1-10.

Significant increase in yields have been obtained when leaves of oil palm were < 0.135 percent sulfur. Optimum level seems to be 0.20 to 0.22 percent.

Olson, R. A. and O. P. Engelstad. 1972. Soil phosphorus and sulfur. In National Academy of Sciences, Soils of the Humid Tropics, Washington, DC.

Total sulfur in tropical soils are discussed as well as responses of crops to applied sulfur and efficiency of fertilizers. Includes large number of references.

Robertson, W. K. and T. L. Yuan. 1974. Effects of phosphorus and sulfur on yield and mineral content of soybeans (Glycine max L.) and white clover (Trifolium repens L.). Soils and Fertilizers 37(8):232.

Soybeans followed by white clover were grown in a fine sand and fine sandy loam in greenhouse, fertilized with S and P at constant levels of N, K, and Ca. Increasing S level increased soybean yields in the fine sand but not in the fine sandy loam while P increased yield in both soils. White clover yield were not increased significantly.

Sedl, J. M. 1973. Sulfur nutrition studies with sugarcane. Fertilizers Abstracts 6(11):281.

Uptake of sulfur by plants was influenced by soluble and adsorbed sulfate in the soil but serious deficiency did not occur.

Shukla, P. and A. N. Pathak. 1973. Effect of molybdenum, phosphorus and sulfur on the yield and composition of berseen in acid soil. Soils and Fertilizers 37(7):198.

Phosphorus and molybdenum increased yield and phosphorus and molybdenum of Trifolium alexandrinum. Elemental sulfur decreased P and Mo concentration in the crop when applied alone but not when P + Mo + S was applied.

Singh, H. G. 1970. Effect of sulfur in preventing the occurrence of Chlorosis in peas. Agron. Jour. 62(6):708-711.

Grain yield of peas increased 100 percent after application of 250 kg S/ha in a field test where plants without S showed Chlorosis.

Sumbak, J. H. 1974. Use of fertilizer in coconut seedling establishment in a grassland area of New Britain. Soils and Fertilizers 37(4):108.

The effect of nitrogen plus sulfur on seedling growth was observed but sulfur alone had little initial effect.

Venkateswarlu, J. I. 1972. Direct and residual effects of sulfates in crop production. Inst. Symp. Soil Fert. Evaluation, New Delhi, 1972.

Mustard and onions as a following crop were both benefited by sulfate application. Sulfur utilization varied from 10 to 57 percent of applied sulfur.

Vogt, J. B. M. 1966. Responses to sulfur fertilization in Northern Rhodesia. Agrochimica 10(2):107-113.

Maize response to sulfur was found in extensive areas with yield increase up to 500 percent when 25 lb/acre of flowers of sulfur was applied with urea or calcium ammonium nitrate.

AVAILABILITY OF SULFUR

Ensminger, L. H. and F. R. Freney. 1966. Diagnostic techniques for determinating sulfur deficiencies in crops and soils. Soil Sci. 10:283-290.

Foliar diagnosis, soil extractants, "A" value and incubation techniques as methods of estimating sulfur status in soils are discussed.

Fortini, J. S., G. Cardas, and S. Panella. 1966. Quantitative evaluation of the available sulfur fraction and soil reserves and of their rate of regeneration. Soils and Fertilizers 29(6):518.

Extraction of soluble sulfate by $CaCl_2$ and adsorbed sulfate by $CaCO_3$ is used for estimation of this and other forms of sulfur in soils and rate of regeneration is followed by $S^{35}O_4^{=}$. The daily rate of regeneration of available $SO_4^{=}$ amounts 2.7 μg to 4.6 μg of S in volcanic soils and humus soils respectively.

Janssen, K. A. and M. L. Vitosh. 1974. Effect of lime, sulfur and molybdenum on N_2 fixation and yield of dark red kidney beans. Agronomy Jour. 66(6):736-740.

Yield response to sulfur was 26 percent without lime and 10 to 12 percent with lime. Liming increased the level of available S in the soil.

Pal, A. R. and D. P. Motiramani. 1971. Evaluation of some soil test methods for measuring available sulfur in medium black soils. Int. Symp. Soil Fertil. Evaluation, New Delhi, Vol. 1:297-307.

Medium black soils of Jabalpur have very little adsorbed sulfate and low sulfate adsorption capacity. Several methods were correlated with sulfur uptake by plants, Morgan's reagent showing highest correlation.

Till, A. R. and G. J. Blair. 1974. Sulfur and phosphorus cycling. Trans. 10th Int. Congr. Soil Sci. Moscow, II:153-157.

Rate of transfer from unavailable to available forms is considered as a test for P and S power supply of soils.

Tisdale, S. L. 1971. Soil and plant test for the evaluation of the sulfur status of soils. Int. Symp. Soil Fert. Evaluation, New Delhi, Vol. I: 119-133.

A review of literature on soil, biological and plant test for available soil sulfur is presented.

Walker, D. R. and G. Doornebal. 1972. Soil sulfate. II. As an index of the sulfur available to legumes. Soils and Fertilizers 35(6):662.

Extractable sulfate in the 0 to 30 cm layer of soil was 86 percent accurate in detecting S deficiencies in available S for legume growth.

SULFUR ABSORPTION BY PLANTS

Barrow, N. J. 1970. Sulfate adsorption by soils as a determinant of sulfur status and methods of applying sulfur on nonadsorbing soils. Proc. Int. Grassland Congress 11th. 370-373.

Soils that adsorb sulfate and have large amounts of sulfate seldom respond to sulfate. Nonadsorbing soils show reponse to applied sulfate. Sulfur is a better source than gypsum because it is more slowly oxidized.

Bromfield, A. R. 1973. Uptake of sulfur and other nutrients by groundnuts (Arachis hypogaea) in north Nigeria. Fertilizer Abstracts 6(4):101.

The highest daily average uptake was 0.22 kg/ha during the eighth week. At harvest time 11.6 kg/ha S were in the plants from which 5.4 was in the haulm, 0.8 in shell and 5.4 in kernels.

Faller, N. 1973. Sulfur dioxide, hydrogen sulfate, nitrous gases and ammonia as sole source of S and N for higher plants. Fertilizers Abstracts 6(1):23.

Higher plants can use SO_2, H_2S, nitrous gases and NH_3 as only source of S or N without affecting normal growth during the whole vegetation period. Sulfur or nitrogen taken from gases were translocated to the roots.

Freney, J. R. and K. Spencer. 1967. Diagnosis of sulfur deficiency in plants by soil and plant analysis. J. Aust. Inst. Agric. Sci. 33(4):284-288.

Plants are not able to use directly organic forms of S which are associated with organic or mineral colloids in soil. These forms must be converted to inorganic sulfate or simpler organic forms.

Hasan, S. M., R. L. Fox and C. C. Boyd. 1970. Solubility and availability of sorbed sulfate in Hawaiian soils. Soil Sci. Soc. Amer. Proc. 34:897-901.

Highly weathered and leached subsoils may contain 7000 μg SO_4-S/g soil in some volcanic ash soils. Some of the less-weathered ash soils are almost devoid of sulfates. For Kikuyo grass soils with large amounts of adsorbed SO_4-S should contain about 5 ppm S in solution for adequate nutrition, after pot experiments.

Jones, H. P., D. W. Cowling, and D. R. Lockyer. 1972. Plant-available and extractable sulfur in some soils of England and Wales. Soil Sci. 114(2):104-114.

The higher levels of available S in soils of the wet region were due mainly to their greater retention of sulfate by adsorption rather than to any difference in previous S input though rainfall and fertilizer.

Pasricha, N. S. and N. S. Randhawa. 1975. Sulfur nutrition of crops from native and applied sources. Soils and Fertilizers 38(9):272.

Native S uptake by soya beans and mustard was increased by low rates of applied sulfur.

Sedl, J. M. 1972. Sulfur nutrition studies with sugarcane. Soils and Fertilizers 35(3):339.

Field experiments with different levels of gypsum in several soils did not show effect of sulfur on sugarcane yield but the amount of sulfur removed increased with increasing levels of adsorbed sulfate in the soil.

SULFUR DEFICIENCIES IN PLANTS

Grant, P. M. and T. F. Shaxson. 1970. The effect of ammonium sulfate fertilizer on sulfur content of tea garden soils in Malawi. Trop. Agric. 47(1):31-36.

Virgin soils of tea plantations in Malawi are deficient in sulfur having little total or available sulfur to four feet depth.

Hardy, Frederick. 1962. Problemas de fertilizacion en el Campo Cerrado de la parte central oriental de Brasil. Turrialba 12(2)128-133.

Phosphorus is the most deficient available nutrient but exchangeable Ca was particularly low and notably S, Zn and Mo. Response to sulfur was observed in pot and field experiments.

Kamprath, E. J. 1973. Sulfur. In P. A. Sanchez (ed.), A Review of Soils Research in Tropical Latin America. Tech. Bul. No. X 219, North Carolina Agricultural Experiment Station.

Soils of Central Plateau of Brazil are deficient in sulfur especially in soils of the upland savannas probably due to repeated burning. Soils high in organic matter may supply initially some sulfur through mineralization. In volcanic soils the stable condition of organic matter does not release sulfur. Latosols and volcanic ash soils adsorb sulfate and may supply adequate sulfate to plants.

Muller, L. E. 1965. Sulfur deficiency in some soils of Central America. Turrialba 15:208-215.

Tomato plants used as indicator show significant response to sulfur applications on coffee soil and a cotton-field soil from El Salvador. Significance of the results to other parts of Central America is discussed.

Ollagnier, M. and R. Ochs. 1972. Sulfur deficiencies in the oil palm and coconut. Oleagineaux 27(4):193-198.

Coconut growing in a savannah of Madagascar after mechanical destruction of Imperata showed deficiences that compromises the survival of young plantations. In Ivory Coast oil palm showing sulfur deficiencies improved growth and early yield after correction of deficiency.

Olson, R. A. and O. P. Engelstad. 1972. Soil phosphorus and sulfur. In National Academy of Sciences, Soils of the Humid Tropics, Wasington, D.C.

Responses to sulfur have been extensively recognized on acid soils of the Campo Cerrado on Brazil, on soils of Punjab of India, East Africa and West Africa and Caribbean Islands. In Southeast Asia the use of ordinary superphosphate and ammonium sulfate have masked the need of sulfur.

Patel, K. S. and N. J. Sawarkar. 1975. Available sulfur status of shallow and deep black soils of Madhya Pradesh. Soils and Fertilizers 38(9): 272.

Based on critical levels of available sulfur, percent deficient soils are given for Chhindwara soils.

Richard L. 1972. Sulfur deficiencies in certain typical crops. A review of the conditions under which they occur and develop. Int. Symp. on Sulfur in Agriculture, Versailles, 1970. Annales Agronomiques. Numero hors Serie, 1972.

Evidence of deficiency, use of foliar analysis, responses to sulfur and other aspects of sulfur deficiency and requirements are examined for peanuts, coconuts, cotton, coffee, cocoa trees, and tropical fruit crops.

Santhirasegaram, K. 1967. Studies on the nutritional status of some coconut soil in Ceylon. IX. The Marine Sandy Soils at Irranawilla. Trop. Agric. 44(3):193-207.

Two types of soils were studied in pot experiments for nutrient status. Both soils were found to be deficient in nitrogen, phosphorus, potassium, and sulfur.

Watson, K. A. 1964. Les engrais en Nigeria du Nord, utilization actuelle et recommendation d'emploi. Sols Africains, IX(1) 21-38.

The total sulfur content of soils varies from 18 to 132 ppm and it has been shown that sulfur represents a limiting factor of growth in peanuts and soybeans and probably other crops, mainly legumes. The application of gypsum was not required when ordinary superphosphate has been used.

Williams, C. H. 1973. Sulfur deficiency in Australia. Sulfur Institute Journal (1972) 8(3):5-8.

Sulfur deficiency in the Northern Territory, Western Australia and Eastern Australia are signaled. Response to sulfur fertilizers and soil test for sulfur are studied.

MOBILITY OF SULFUR IN SOILS

Gachon, L. 1972. Sulfur losses by drainage. Int. Symp. on Sulfur in Agriculture, Versailles, 1970. Annales Agronomiques, Numero hors Serie, 72-1:11-21.

Lysimeter studies inthe Massif Central in France showed annual losses of 12 to 102 kg/ha of sulfur. More sulfur was lost from fallow land than from cultivated land. Perennial or long-term forage crops showed smaller losses than annual crops.

Gillman, G. P. 1973. Studies on some deep sandy soils in Cape York Peninsula, North Queensland. III. Losses of applied phosphorus and sulfur. Soils and Fertilizers 37(3):47.

Ten to thirty percent of sulfur applied was recovered in the 100 cm profile. Phosphorus and sulfur leached to greater depths are still available.

Haque, I. and D. Walmsley. 1974. Movement of sulfate in two Caribbean soils. Plant and Soils 40(1):145-152.

Leaching studies in an Andept and Mollisol show that in the first one sulfate from K_2SO_4 was retained in the top 15 cm where 20 cm of water was applied while in the Mollisol SO_4 accumulated in the lower end of the column. These differences were attributed to different sulfate retentive properties.

Hogg, D. E. and M. R. J. Toxopeus. 1966. Studies on the retention of sulfur by yellow-brown pumice soils. New Zeal. Jour. Agric. Res. 9:93-97.

Leaching losses of SO_4 from added superphosphate were 33 to 100 percent of that applied in 40 yellow-brown pumice soils. Only 2 to 6 percent losses were observed in some yellow-brown loams. Allophane retention appears to be an important factor.

Khan, S. V. and G. R. Webster. 1968. Sulfate distribution in solonetzic soil with a water table. Jour. Soil Sci. 19:20-24.

SO_4 distribution in different horizons of a loam soil was studied by a column technique and $^{33}SO_4$. Upward movement of SO_4 from the water table was observed but SO_4 moves more slowly than water in soil. The highest SO_4 levels were in the 10 to 12.5 cm layer when water reached the surface.

Rhue, R. D. and E. J. Kamprath. 1973.

Leaching losses of sulfur during winter months when applied as gypsum, elemental sulfur or prilled sulfur. Agron. Jour. 75(4):603-605.

Leaching of SO_4 occurs in sandy soils of the southeastern United States, often deficients in sulfur. To maintain adequate supply of sulfur several sources were studied. Almost all of the sulfate applied as gypsum and that resulting from the oxidation of elemental sulfur had been leached from the top 45 cm of Wagram soil 180 days after application. In Georgeville soil there was essentially no movement of sulfate. Finally divided elemental sulfur appeared to be completely oxidized after 200 days but very little oxidation of prilled sulfur occurred.

Swoboda, A. R. and G. W. Thomas. 1965. The movement of sulfate salts in soils. Soil Sci. Soc. Amer. Proc. 29:540-544.

Movement of adsorbed sulfate from K_2SO_4 in columns was observed to correspond to the movements of exchangeable cations. Extensive leaching with 105 to 207 inches of distilled water caused displacement of adsorbed SO_4 as well as of potassium and calcium.

Williams. C. H. 1971. Reaction of surface-applied superphosphate with soil. II. Movement of the phosphorus and sulfur into the soil. Australian Jour. Soil Res. 9(2):95-107.

Movement of SO_4 from surface applied superphosphate was governed by particle size of fertilizer and soil moisture both of which influenced rate of solution of $CaSO_4$. SO_4 sorption capacity of the soil influenced distribution. In acid soils SO_4 penetrates more quickly than in calcareous soils.

TRANSFORMATIONS OF SULFUR IN SOILS

Ahmeu, I. U. and K. M. Idris. 1968. Effect of nitrogen, phosphorus, and potassium on the transformation of organic sulfur in acid and calcareous soils at different moisture levels. Soils and Fertilizers 31(6):478.

Incubation of two soils samples with addition of city-waste show accumulation of water soluble SO_4, thiosulfate and SO_3 when nitrogen,

phosphorus or potassium was also applied. Production of these compounds was greater at field capacity than at half field capacity or under completely water logged conditions. H_2S produced was larger with waterlogging. Organic sulfur was considerably lower in NPK-treated soils.

Durand, J. H. 1974. The geochemistry of tidal basin soils. General consideration and reclamation. Soils and Fertilizers 37(4):95.

Chemical and biological transformations with particular reference to sulfur and clay minerals in soils periodically flooded by sea water was studied.

Engler, R. W. and W. H. Patrick, Jr. 1973. Sulfate reduction and sulfide oxidation in flooded soil as affected by chemical oxidants. Soils Sci. Soc. Amer. Proc. 37(5):685-688.

O_2, KNO_3, MnO_2, ferricitrophosphate and $FePO_4$ effects on SO_4 reduction and sulfur oxidation were studied in a previously reduced soil. The more soluble oxidants had the greatest effects in delaying SO_4 reduction. The less soluble oxidants preserved longer sulfur buildup.

Evans, H. 1968. Toxic sulfate soils and their improvement for sugarcane cultivation. Soils and Fertilizers 31(4):303.

Sulfur compounds of aluminum and iron caused toxicity to sugarcane in some Guyanan soils which are submerged naturally in water and have pH values as low as 2.5 when drained and oxidized.

Gotoh, S. and K. Yamashita. 1966. Oxidation-reduction potential of paddy soil in situ with special reference to the production of ferrous iron manganous manganese and sulfide. Soil Sci. Plant Nutrit. 12(6):230-238.

The level of compost enhanced increase in Mn^{++}, Fe^{++}, and S^{--} and have injurious effect on rice. Eh values at which reduced forms begin to develop are given.

Grant, P. M. and T. F. Shaxson. 1970. The effect of ammonium sulfate fertilizer on the sulfur content of tea garden soils in Malawi. Trop. Agric. 47(1):31-36.

"Tea yellows" are developed in soils deficient in sulfur and sulfate fertilizers have been used for many years to prevent this effect. Ammonium sulfate application results in an increase in adsorbed and organic sulfur to 2 ft depth after 30 years but little accumulation occurs below 3 ft.

Jacq, V. A. 1974. Biological sulfate-reduction in the spermosphere and the rhizosphere of rice in some acid sulfate soils of Senegal. Soils and Fertilizers 37(8):207.

Anaerobic conditions in the topsoil favor proliferation of sulfate-reducing bacteria. Germinating seeds and seedling roots activates H_2S production.

Sachdev, M. S. and P. Chhabra. 1974. Transformation of S^{35} labeled sulfate in aerobic and flooded soil conditions. Plant and Soil 41(2):335-341.

After four months incubation under flooded conditions 56 percent of added sulfate was present as SO_4, organic, humus, amino acid, and evolved H_2S. In aerobic conditions 99 percent was found in these forms.

Simon-Sylvestre, G. 1972. Sulfur in soils, its evolution. Inter. Symp. on Sulfur in Agriculture, Versailles, 1970. Annales Agronomiques Numero hors Serie, 72-1, 181-199.

The sulfur cycle is considered and the effects of soil type on the mineralization of organic sulfur. Mineralization decreases in the order; loamy clay, sandy soils, rendzina, and some acid soils.

Thornton, I. and E. C. Giglioli. 1966. The mangrove swamps of Keneba, Lower Gambia River basin. II. Sulfur and pH in the profiles of swamp soils. Soils and Fertilizer 29(3):266.

Water soluble S, SO_4, and free S concentration in soil profiles were studied under three different plants. The effect of fluctuation of water table on pH of dried soils is considered.

Yamane, I. 1969. Reduction of nitrate and sulfate in submerged soils with special reference to redox potential and water-soluble sugar content of soil. Soil Sci. and Plant Nutr. 15(4):139-148.

Reduction of nitrate and sulfate was studied in laboratory and field conditions with special reference to the redox potential and water soluble sugars of the soils.

ATMOSPHERIC SULFUR INPUTS

Bromfield, A. R. 1974. The deposition of sulfur in the rainwater in Northern Nigeria. Soils and Fertilizers 38(5):114.

Amount of sulfur deposited was 0.49 to 1.89 kg S/ha being greater at the beginning and end of the rainy seasons.

Junge, Chr. 1972. Sulfur supplies of atmospheric origin. Int. Symp. on Sulfur in Agriculture, Versailles, 1970. Annales Agronomiques, Numero hors Serie, 72-1, 235-247.

Riehm, H. 1966. Plant nutrients in atmospheric precipitation with particular reference to sulfur. Soils and Fertilizers 29(3):238.

In central Europe the sulfur content was 1 to 1.5 mg/l but in coastal and highly populated areas it increased to 2.1 to 3.6 mg/l. In central Europe the supply of sulfur from atmospheric rainfall and fertilizers exceeds removal by leaching and harvest but in northern and southern Europe removal exceeds supply.

Seim, E. C., A. C. Caldwell and G. W. Rehm. 1969. Sulfur response by alfalfa (Medicago sativa L.) on a sulfur deficient soil. Agron. Jour. 61:368-371.

Average annual sulfur addition to the soil from atmospheric sources ranged from 5.4 kg/ha in a rural area to 27.4 kg/ha in a metropolitan area of Minnesota.

MISCELLANEOUS

Andreis, H. J. and G. J. Gascho. 1971. Improving manganese nutrition of sugarcane grown on high pH organic soils. Soils and Fertilizers 37(2):38.

Sulfur fertilizing corrected manganese deficiencies and increased yield.

Godefroy, J. and P. H. Melin. 1974. 1974. Effect of sulfur addition on chemical characteristics of volcanic soil of banana plantations. Fertilizer Abstracts 7(1):21.

Exchangeable calcium and potassium were reduced by application of sulfur at several levels of applied nitrogen as urea. Ammonification was not affected but nitrification of urea was retarded.

Lindell, D. L. and R. C. Sorensen. 1974. Sulfur and manganese release from soils treated with prilled sulfur and sulfur-bentonite. Soil Sci. Soc. Amer. Proc. 38(2):368-372.

Sulfate-sulfur, manganese and hydrogen released to a leaching solution after successive incubation was studied in seven Nebraska soils.

Miyamoto, S., H. L. Bohn, J. Ryan, and M. S. Yee. 1974. Effect of sulfuric acid and sulfur dioxide on the aggregate stability of calcareous soils. Soil Sci. 118(5):199-303.

The effect of H_2SO_4 and SO_2 on aggregate stability was studied in two noncalcareous, two sodic-calcareous and six calcareous soils. The sorption of SO_2 from moist streams reduced aggregate stability but less than equivalent amount of H_2SO_4 solutions.

Ofori, C. S. 1973. Influence of nitrogen and sulfur on the absorption of fertilizer phosphorus and the yield of groundnut grown on soil of granitic origin. Oleagineux 28(1):21-23.

Sulfur or nitrogen did not affect P_2O_5 derived from fertilizer in the forage but 34 kg S as Na_2SO_4 added to 50 kg P_2O_5/ha significantly lowered kernel yield.

Shevyakova, N. I. 1974. Consequences of sulfur deficiency on the mineral balance in cotton under conditions of sodium chloride salinity. Fertilizer Abstracts 7(9):231.

Cotton plants require more potassium and sulfur when affected by NaCl salinity was showed by pot experiments.

Stewart, B. A., L. K. Porter and F. G. Viets, Jr. 1966. Sulfur requirements for decomposition of cellulose and glucose in soils. Soil Sci. Soc. Amer. Proc. 30: 453-456.

In soils adequately supplied with nitrogen and phosphorus the rate of decomposition of cellulose and glucose depends on sulfur levels.