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Soil Sulphur status and response of crops to Sulphur application in Indian soils: A review

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Abstract
Sulphur deficiency is becoming serious problem mainly because of incorporation of high yielding varieties of crops in multiple cropping system, continuous use of Sulphur free fertilizers, insecticides and fungicides for crop production resulting in exhaustion of soils of Sulphur. Soil Sulphur status varies due to variation in soil forming factors like parent materials, climatic conditions, degree of weathering, amount of organic matter etc. Normal agricultural soils in India content total Sulphur in the range of 50 to 300 mg kg^{-1} available Sulphur status of soil indicated that available Sulphur in Indian soil varied from as low as traces to as high as 800 mg kg^{-1}. It has become increasingly clear that oilseed require Sulphur in higher amount followed by pulses forages, tuber crops and cereals. Results of Sulphur researches revealed that response of crops to Sulphur application is highly location specific; available S status, genotypes, growth conditions and crop management level dependent, whose optimum level has to be established based on local condition. Sulphur uptake varied depending on the crop and its variety, its yield level, cropping intensity, rates of Sulphur application, soil Sulphur status and status of other major nutrients particularly nitrogen and phosphorus.

Keywords: Sulphur, fertilizers, insecticides and fungicides

Introduction
In recent years, Sulphur deficiency is becoming serious problem mainly because of incorporation of high yielding varieties of crops in multiple cropping system, continuous use of Sulphur free fertilizers, insecticides and fungicides for crop production resulting in exhaustion of soils for Sulphur. Such situation reflected its adverse effect on crop production and as such the scientists working on Sulphur nutrition and its chemistry in soil-plant system were forced to be attracted towards Sulphur research. The information available on some important aspects of Sulphur research like response of crops to Sulphur application, increasing the efficiency of Sulphur containing fertilizers by several methods including amendment with organic manures, its transformation and movement in the soil and its kinetics of adsorption and desorption was found to be meagre. The behaviour of Sulphur, as appears from the literature, is highly specific to the physical and chemical properties of soils as well as nature of crops grown on them. Some of the important results on the above aspects available in the literature have been reviewed, compiled and are being presented here.

Sulphur status of soil
Total Sulphur
There is a wide variation in the distribution of total soil Sulphur in Indian soils probably due to variation in several soil forming factors like parent materials, climatic conditions, degree of weathering, amount of organic matter etc. Generally, soil S is highest in the top soil and decreases with depth following the pattern of organic matter distribution. However, this pattern does not occur where sulphates get accumulated in lower layers (Takkar, 1988) [30]. The total S content in surface soils of India varied from as low as less than 20 mg kg^{-1} to as high as 9750 mg kg^{-1}. Most normal agricultural soils contain total S in the range of 50 to 300 mg kg^{-1} through certain alluvial soils of Bihar contain 471 to 851 (Av. 576) ppm (Tandon, 1991) [31].

Available sulphate Sulphur
Sulphate Sulphur is generally referred as available Sulphur. Plant roots absorb S in the form of sulphate ions (SO_4^{2-}) from the soil. The pool of sulphate-S consisting of water soluble, adsorbed and easily released from organic matter has an important bearing on the Sulphur nutrition of crops.

Generally, available-S in Indian soils is less than 10% of total S. However, it can vary from 1% in certain acid soils upto 55% of total S as found in a paddy soil. The results summarized by Hegde *et al.* (1980) [7] confirm that more than 10% of the total S are extracted as available-S in hilly red and alluvial paddy soils. Mahto *et al.* (1992) [11] measured the total and available Sulphur in some soils of Chhotanagpur area of Bihar (now in Jharkhand), and reported that available-S was higher in alkaline soils while total S was highest in acidic soils. Singh *et al.* (1993) [26] reported that in some soils of Chhotanagpur, the soluble sulphate-S in the soils formed a small fraction (1.25%) of the total S and got nearly 60 per cent soil deficient in S. This was probably due to leaching losses of SO_4-S in these coarse textured soils.

Sulphur deficiency was found to be higher in coarse texture soil than the fine texture soils. Available-S decreased with increase in pH and decrease in organic carbon and available-P content of soils.

Sulphur concentration in plants

Sulphur requirement of different crops varied greatly depending on the genetical character of the crops. Even in the same crop species, different varieties varied greatly in their Sulphur content. In general S content was found to be more in oilseeds and pulses as compared to cereal and other crops. Aulakh *et al.* (1985) [3] estimated that concentration of S is higher in the grains than in straw with the widest differences in cruciferous crops and smallest in legumes. They got 1.19% S in seeds and 0.13% in straw of cruciferous crops. Reddy *et al.* (1988) [18] reported that Sulphur content of cereal plants is generally in the range of 0.16% - 0.25% and less than 0.20% is considered as sub optimal for most cereals. Sharma (1991) [21] studied Sulphur concentrations in a rice-wheat rotation under optimum fertilization in grain & straw and observed that rice contained 0.17% S in grain and 0.13% S in straw while wheat contained 0.26% in grain and 0.24% S in straw.

Response of crops to Sulphur application

Crop yield

Several field experiments have been conducted in the country by different workers to show the yield responses of different crops to S application. Mean yield increases due to S application are in the range of 638 to 813 kg ha^{-1} for cereals, 168 to 428 kg ha^{-1} for pulses and 144 to 566 kg ha^{-1} for oilseeds (Tandon, 1995) [32]. According to him the average per cent yield responses to S for crops grown in S-deficient soils were 17.1% in rice, 25.3% in wheat, 30.0% in rapeseed-mustard and 31.7% in groundnut. Earlier, some of the results on yield responses of cereals, millets and oilseeds were also summarized by Tandon (1991) [31]. State-wise analysis shows that significant responses to the application of 20-30 kg S ha^{-1} usually as gypsum but also ammonium sulphate were obtained in 77% trials in U.P., 62% in Madhya Pradesh, 50% in Gujarat and Punjab and 30% in Haryana. Among main crops, significant response to S was recorded in 77% cases in soybean, 67% in wheat, 57% in rice, 55% cases in mustard and 33% cases in groundnut. Trends of response with increasing levels of S indicate that rates above 30 kg S ha^{-1} would have given an additional yield increase, particularly in the case of rice, wheat and mustard whereas 30 kg S ha^{-1} appears closer to optimum for groundnut and soybean.

Seed and straw yield increased significantly with increasing level of Sulphur upto highest level of 60 kg S ha^{-1}; application of 20, 40, and 60 kg S ha^{-1} increased the seed yield over the control by 13.9%, 28.1 and 28. 4% respectively (Kumar and Trivedi, 2012) [10]. Treatments containing 100% of recommended dose of fertilizers and NPK + FYM 5 MT ha^{-1} + 40 kg S ha^{-1} recorded significantly highest grain yield (17.96 q ha^{-1}), oil yield (6.72 q ha^{-1}) and stover yield (43.7 q ha^{-1}) over other treatments (Singh *et al*., 2017) [22].

The seed and stover yield of mustard increased in the linear order up to 60 kg ha^{-1} but significant increase was obtained up to 30 kg ha^{-1} which was 21.4 percent higher in the comparison to the yield obtained in control (Kaur *et al*., 2014) [9].

Sulphur application significantly increased the mustard seed and stover. The optimum level of Sulphur was worked out to be 60 kg S ha^{-1} for mustard seed and stover production. However, with regards to total Sulphur uptake the optimum dose appeared at 100 kg S ha^{-1} (Rakesh *et al*., 2020) [16].

In calcareous soils of north Bihar, applications of 20 to 40 kg S ha^{-1} appreciably increased crops yield. In rice, wheat and maize, the grain yield response at 40 kg S ha^{-1} ranged from 29.4 to 33.0 per cent and in sugarcane the cane yield response of 32.4% was noted at 80 kg S ha^{-1} (Sakal *et al*. 1996) [19]. Mishra (1995) [12] studied the response of S on rice, mustard, groundnut and safflower in red, lateritic and black soils of Orissa. The dose of S varied from 15-30 kg ha^{-1} and grain yield response from 14.5 (rice) to 77.6 (Safflower) per cent. On the basis of per cent yield response (figures in parentheses), the crops may be arranged as rice (14.5) < mustard (47.0) < groundnut (53.6) < Safflower (77.6). Aulakh and Pasricha (1988) [2] observed the Sulphur response in mustard and found that S application increases the yield of mustard by 12 to 48% under irrigated and 17 to 24% under rainfed conditions. Application of 20 to 40 kg S ha^{-1} brings a modest 10 to 20% increase in yield in S deficient soils. In case of toria, S application was found to increase oilseed yield and the increase in yield was found to vary from 1.2 q ha^{-1} in Uttar Pradesh to 5.9 q ha^{-1} in Punjab with 20 kg S ha^{-1}.

The response of S fertilizer in mustard on S deficient soil has also been reported in recent literature from most of the states of India irrespective of texture and genetic make-up of soil but the rate at which the highest yield response was obtained differed widely according to locations. The response of Sulphur applied through superphosphate, gypsum, press mud and pyrites was studied on mustard on a sandy soil by Narwal *et al.* (1991) [13]. Grain/ stalk yield and oil yield of mustard increased significantly with increasing levels of Sulphur. Among the various sources of S tested, gypsum was the best in respect of both grain and oil yield. Next in order were single super phosphate, press mud and pyrites. The poor response to pyrites might be due to low oxidation rate of sulphide to form sulphate which is controlled by moisture, temperature and microbial activity. The efficiency of these fertilizers based on total S uptake, was 56.4, 49.0, 35.5 and 11.7% for gypsum, single superphosphate, press mud and pyrites, respectively. Singh and Chhibba (1991) [23] reported the effect of different Sulphur carriers on the dry matter yield in maize and wheat on a sandy loam soil. Sulphur application increased the dry matter yield of maize and wheat significantly over control. For maize, ammonium sulphate, single superphosphate, gypsum and elemental S proved equally effective. For wheat on the other hand, ammonium sulphate was the most efficient. Superphosphate was significantly better than elemental S and pyrite but remained at par with gypsum. Out of the sulphate sources, ammonium sulphate proved to be the most efficient for both maize and wheat owing to the high solubility of ammonium sulphate.

Efficiency of different Sulphur carriers to peanut, maize and wheat on an alkaline sandy soil was reported by Arora *et al.*

(1991) [1]. Based on the availability coefficient ratios (ACR), elemental Sulphur was found to be least effective among all the four Sulphur carriers. Gypsum and superphosphate generally performed better than sodium sulphate. The elemental Sulphur added to the soil is subjected to microbial transformation in SO_4 -S before it is taken up by the plants.

Ram and Dwivedi (1992) [17] reported that the straw yield of chickpea increased to the tune of 21.3 and 19.3 per cent over control during the first and second year, respectively. Gypsum was the best source for increasing grain and straw yields. Higher response of gypsum to grain and straw might be due to presence of readily available sulphate Sulphur in gypsum compared to other two source. Similar observations were also made by Sharma *et al.* (1991) [20]. Further, Sharma *et al.* (1991) [20] while working on different doses and sources of Sulphur application in alkaline soil of Madhya Pradesh under the prevailing soil and climatic conditions obtained 60 kg S ha^{-1} as the optimum S level for obtaining the highest oil content, seed and oil yield and protein content of mustard crop.

The direct effect of pyrite and organic manures on grain yield of lentil crop was reported by Sinha and Sakal (1993a) [27]. They reported that pyrites, pressmud and FYM application either alone or in combination significantly increased the lentil yield. The pyrite application along with organic manure was more effective as compared to pyrite alone. They suggested that organic manure has increased the efficiency of pyrite as a source of S. Patel and Patel (1994) [14] portrayed the effect of Sulphur on dry matter yield of lucern on an alluvial soil at Anand. They reported that application of 80 kg ha^{-1} produced significantly higher dry matter yield (138.0 q ha^{-1}) over no S application. The response to applied S was more where available-S in soil was low.

Influence of native and applied Sulphur on yield of sunflower at different stages of growth was studied by Sreemannarayana and Sreenivasa Raju (1994) [29] using ^{35}S labelled sources under field conditions on Sulphur deficient Vertisols and Alfisols with four doses of Sulphur. There was decrease in dry matter yield with the increase in S levels upto 60 kg S ha^{-1} in Alfisols, in case of Vertisol, the increase in yield was observed only upto 40 kg S ha^{-1} level. The reduction in dry matter yield at 60 kg S ha^{-1} level might be due to toxic effects of SO_4^{2-} accumulation in plant tissues. In Alfisol, however, such decrease was not seen, probably because of higher requirement of S in these light textured soils, as SO_4^{2-} is often subjected to leaching loss and only a limited quantity of applied S is made available for plant utilization. In general, the dry matter yields recorded in vertisols were higher as compared to those in Alfisol, which might be due to difference in fertility status of soil. Significant increase in toria yield upto 45 kg S ha^{-1} level was also reported by Das and Das (1994) [5]. Similarly, the effect of S on grain and straw yield of gobhi sarson were also reported by Biswas *et al.* (1995) [4]. They observed that addition of S enhanced the grain and straw yield of gobhi sarson. However, the effect was limited to the S application upto 50 kg ha^{-1}, beyond which the response showed declining trend in grain yield, whereas, significant increase of straw yield was observed upto 75 kg S ha^{-1} application. The increase in dry matter production may be because of higher rate in protein synthesis and enhanced photosynthetic activity of the plant with increased chlorophyll synthesis due to fertilization with Sulphur.

Relative efficacy of Sulphur carriers on yield of blackgram was advocated by Dwivedi *et al.* (1996) [6]. Sulphur application through various carriers increased the grain yields of Blackgram significantly to the extent of 19.6 and 20% over control during 1992 and 1993, respectively. Similarly, straw yield was also increased significantly and magnitude of this increase was 17.3 and 20% over control during both respective years. Gypsum was found to be the best source for increasing grain and straw yields. This might be due to the presence of readily available SO_4-S in gypsum as compared to other two sources i.e. pyrite and elemental S.

Based on a field experiment conducted on loamy typic ustochrept of U.P., Tripathi *et al.* (1997) [33] reported that chickpea responded significantly to the application of S. The highest grain yield recorded at 40 kg S ha^{-1} was found about 22 to 23 per cent higher than control. The increase in grain yield on addition of S was due to the S deficient soil of the experimental field.

Sulphur fertilization for increased production of summer moong (Vigna radiata L.) was reported by Singh *et al.* (1997) [24]. Summer moong was grown in field for two years with application of elemental Sulphur (0, 15, 30 and 45 kg ha^{-1}) on Inceptisol (Udic ustochrept). Sulphur application improved significantly plant biomass, nodule number and weight, seed and straw yield, nitrogen and Sulphur uptake, optimum being 30 kg ha^{-1}. Application of Sulphur upto 15 kg ha^{-1} increased population of total bacteria and Azotobacter. However, addition of Sulphur decreased the population of fungi and actinomycetes. Decrease in fungal population due to Sulphur application might be due to fungicidal nature of Sulphur whereas the incompatibility of Sulphur with actinomycetes caused the decrease in the number of actinomycetes.

Sulphur content and uptake by crops

Sulphur uptake ranged from 5 to 80 kg S ha^{-1} depending on the crop and its variety, its yield level, cropping intensity, rates of S application, soil Sulphur status and status of other major nutrients particularly N and P.

At present the total Sulphur uptake by crops in India comes to around 1 million tonne. It is projected to be 1.33 million tonnes by the year 2000 (Kanwar and Mudahar, 1985) [8], but could be higher. Annual additions through fertilizer materials are around 0.4 million tonne. The gap between Sulphur additions and its removal is likely to increase and correcting measures are called for Narwal *et al.* (1991) [13] noticed increase in total S uptake upto 120 ppm S application irrespective of the variation in sources of Sulphur. Total S uptake was found to be highest in grain followed by stalk and pod-husk of mustard. The highest S uptake by mustard grain was due to the higher content of S containing amino acids cystine, cysteine and methionine. The highest uptake of S was observed when gypsum was the S source followed by superphosphate, press mud and pyrites. The uptake of N, P, K and S by chickpea due to S application were significantly higher than control as reported by Ram and Dwivedi (1992) [17]. They further recorded highest uptake of N, P, K and S by S application through gypsum. Singh *et al.* (1992) [25] reported that the S content and uptake by black gram and lentil crops increased significantly with increasing pyrite levels. The total S removal by black gram was much higher than that by lentil. Availability of Sulphur in soil increased markedly with the addition of pyrite and consequently total Sulphur uptake by crops increased with increasing pyrite levels. The direct and residual effect of pyrites and organic manures (FYM and sulphitation press mud) were evaluated with respect to S nutrition of crops by Sinha and Sakal, 1993a; 1993b [27, 28]. Based on their results they suggested that pyrite @8 q ha^{-1}

when applied along with 100 q organic manure ha^{-1} was always superior over other treatment combination which might be due to increase in solubility of pyrite.

Sulphur concentration in grain and straw of toria were reported by Raj *et al.* (1994) [15] on loamy sand soil of Hissar. Sulphur content in grain increased significantly with increasing S level upto 45 mg kg^{-1} through pyrite and potassium sulphate and 60 mg kg^{-1} through superphosphate and gypsum. Similarly, in straw, superphosphate and gypsum increase S content upto 60 mg kg^{-1} while other two sources, viz. pyrite and K_2SO_4 did not follow any definite trend. The average values of total Sulphur removal increased with increasing level of S upto 60 mg kg^{-1}. Among different sources of Sulphur, gypsum proved to be better for total Sulphur uptake.

The pattern of Sulphur uptake by three genotypes of sunflower at four growth stages was studied using ^{35}S labelled sources under field conditions on Sulphur deficient Vertisols and Alfisols with four doses of Sulphur by Sreemannarayana and Sreenivasa Raju (1994) [29]. It was reported that Sulphur content of plants increased with S application through different sources viz., gypsum, ammonium sulphate and superphosphate and decreased with progress in plant growth. Sulphur application increased S uptake by sunflower at star, bud, flowering and maturity stages. The ratio of S uptake from native to applied source indicated preferential absorption of soil Sulphur at all levels of applied S. The efficiency of native source of S was high at all the growth stages.

The effect of Sulphur fertilization on S content and uptake of S by grain and straw was reported by Das and Das (1994) [5]. It was observed that increasing level of S increased S content of both grain and stover significantly over control. The application of S increased the amount of S uptake by rapeseed grain significantly except 15 kg ha^{-1}. The Sulphur content increased from 0.415 to 0.499 per cent in grain, 0.150 to 0.241 per cent in straw and consequently its uptake increased from 5.34 to 7.42 kg ha^{-1} with the application of 45 kg S ha^{-1}. The positive response of Sulphur application in terms of S uptake by gobhi sarson (*Brassica napus* L., ISN-706) was restricted upto 75 kg S ha^{-1} level (Biswas *et al.* 1995) [4]. Increased uptake of S by gobhi sarson due to Sulphur treatment could be due to higher demand of the crop for Sulphur.

Conclusion

Results of Sulphur researches revealed that response of crops to Sulphur application is highly location specific; available S status, genotypes, growth conditions and crop management level dependent, whose optimum level has to be established based on local condition. Sulphur uptake varied depending on the crop and its variety, its yield level, cropping intensity, rates of Sulphur application, soil Sulphur status and status of other major nutrients particularly nitrogen and phosphorus.

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