**Annals of Plant and Soil Research 17 (1): 1-12 (2015)**

# SULPHUR MANAGEMENT FOR INCREASED PRODUCTIVITY OF INDIAN MUSTARD: A REVIEW

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Received: Februray, 2014; Revised accepted: November, 2014

## ABSTRACT

*Sulphur (S) is a crucial element for rapeseed-mustard in determining its seed yield, oil content, quality, and resistance to various biotic and abiotic stresses. Besides promoting chlorophyll formation and oil synthesis, it is an important constituent of seed protein, amino acids, various enzymes, and glucosinolate. Sulphur increases the seed yield of mustard by 12 to 48% under irrigated and 17 to 124% under rainfed conditions. In terms of agronomic efficiency, each kilogram of S increases the mustard yield by 7.7 kg. Intensification of agriculture and multiple cropping, coupled with use of high analysis S-free fertilizers and restricted use of organic manures, has accelerated the depletion of soil S reserves. Total S content in Indian soils ranged from 10 to 6319 mg kg$^{-1}$, but mean content is 30 to 300 mg kg$^{-1}$ soil in most of agricultural soils. The increase in oil content of mustard due to S application is associated with the increase activity of an enzyme named acetyl-CoA carboxylase, which is also a precursor for oil synthesis. Sulphur is important for plants in another sense also that it dilutes the harmful effect of heavy metal toxicity caused by cadmium. Interaction of S with other nutrients is both synergistic and antagonistic. The recommendations for specific S fertilization for different zones in mustard based cropping systems have been made under All India Coordinated Research Project on Rapeseed-Mustard (AICRP-RM). In order to increase the S use efficiency, it is not only necessary to apply the correct amount (on soil test basis) in a balanced proportion with other limiting nutrient element in the soil, but it is equally important to apply it at the proper physiological stage of the plant. Although, the best time of S application is basal, but it may be top dressed also at 20-40 days of growth to get good yield. The experiments under AICRP-RM have revealed the higher response of mustard to foliar spray of thiourea at flowering and basal placement before sowing. Other than traditional S fertilizers, fortified S fertilizers, S coated fertilizers, liquid S fertilizers and moreover integrated use of S with organic manure has been proved better. In the present paper, the status of Indian soils, response of S to rapeseed-mustard, mainly Brassica juncea and enhancing S use efficiency through advancement in techniques including rate, method and sources of S have been reviewed.*

**Keywords:** Sulphur, sources, rate, time of application, oil yield productivity, Indian mustard

## INTRODUCTION

Sulphur (S) is one of the essential secondary macronutrient required for the growth, metabolism and development of all plants and is rightly called as the fourth major plant nutrient. S plays a vital role in different physiological and biochemical functions in plants. Sulphur deficiencies have been reported from more than 70 countries over the world, including India. Sulphur promotes oil synthesis, besides being an important constituent of seed protein, amino acid, enzymes, glucosinolate and chlorophyll (Holmes, 1980). Sulphur uptake and assimilation in rapeseed-mustard are crucial for determining yield, oil, quality and resistance to various stresses. Among the oilseed crops, rapeseed-mustard has the highest requirement of S. Sulphur increases the yield of mustard by 12 to 48% under irrigated, and by 17 to 124% under rainfed conditions (Aulakh and Pasricha, 1988). In terms of agronomic efficiency, each kilogram of S increases the yield of mustard by 7.7 kg (Katyal *et al.*, 1997). Rapeseed (*Brassica compestris* and *Brassica rapa L.*) has been observed to require 3-10 times more S than barley (Bole and Pitman 1984). Intensification of agriculture with high yielding crop varieties and multiple cropping, coupled with use of high analysis S-free fertilizers and restricted use of organic manures, has accelerated the deficiencies of S in arable lands. Continuous use of S free fertilizers has widened the ratio of N: $P_2O_5$: $K_2O$: S to 14.7:5.1:1.6:1 in India (TSI, 2014). There is urgent need to bring N: $P_2O_5$: $K_2O$: S to desired level through adoption of advanced techniques developed for sustainable S management. The average productivity of rapeseed-mustard in India is only 1145 kg ha$^{-1}$ which needs to be enhanced up to 2562 kg ha$^{-1}$ by 2030 for ensuring edible oil self reliance (DRMR, 2011). For attaining this productivity level, a comprehensive S management might play a major role. Improved S management will enhance oilseed productivity, especially of rapeseed-mustard through précised fertilizers addressing the deficiencies.

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**Sulphur in soil**

The organic S compounds in the soil constitute up to 98% of the total soil S and it is a heterogeneous mixture of plant residues, animals and soil microorganisms. In many ways, S behaves and reacts in the soil as nitrogen. Like N, S is a mobile nutrient that may move rapidly through the soil, especially through sandy surface layers. Sulfate is negatively charged and is subjected to leaching. Soluble sulfates seldom accumulate in the upper soil layer (30 cm) because they are leached into the B-horizon. Sulphur often accumulates in the sub-soil where soluble Sulphur is absorbed by iron and aluminum oxides. Sulphur accumulation increases as subsoil acidity increases. Sulphur is mineralized from organic matter to sulfate and mineralization depends upon the C: S ratio. The critical range is 200-300:1. If it is < 200:1, then net mineralization and if it is > 300:1, net immobilization occur. Sulfate can be tied up (immobilized) by soil microbes if the residue contains a low amount of S. Sulfate can also volatilize as hydrogen sulfide ($H_2S$) under water logged condition.

Atmospheric S can contribute about 5-10 kg $ha^{-1}$ of S per year. The absorption and translocation of S in the soil depends upon the soil characteristics also. For absorption study, Freundlich adsorption isotherms help in understanding movement and retention of added S in the soil. Among gypsum and $K_2SO_4$ as source of S, $K_2SO_4$ migrates deeper than gypsum. About 28 to 38% of the added S is retained in the 90 cm depth of the profile. Maximum increase in total S content by S application is recorded in upper soil layer. Soluble S accumulation increases in the 30 to 75 cm of depth, where as proportion of sorbed fraction of S increases with depth. Building up of S in the surface layer due to the increase in organic fraction in lower layer of the profile is through increase in soluble and sorbed fraction of S (Saha *et al*. 2002). Total S content in Indian soils ranged from 10 to 6319 mg $kg^{-1}$, but the mean content is found to be 30 to 300 mg $kg^{-1}$ in most of the agricultural soils.

Most of the soils of Indo-Gangetic plains, red, latreitic and hill soils are prone to S deficiency while coastal soils are reported to be adequate in it. Sulphur deficiency is also wide spread in calcareous as well as medium and shallow black clay soils due to low organic matter content. Most of the saline soils and acid sulfate soils of Sundarban areas of West–Bengal and coastal Kerala contain excessive amount of S as sufide or soluble sulfate which causes severe injury in plants. So, there is wide variability in total S content in soils of various states of the country (Singh, 2000). Sulphur deficiency is most likely in coarse-textured soils, low in organic matter, high rainfall areas, crop rotations including pulses and oilseed, continuous use of S-free fertilizers and sites away from industrial activity associated with the emission of S containing gasses. Determining S deficiency is not simple but a combination approach of integrating several factors in to the S deficiency equation can be useful. Like in plants, in soils also there are some indicators, which help in diagnosing deficiency in soil (Tucker, 2002).

**Response of rapeseed-mustard to sulphur**

Sulphur has some specific role in oilseed crops. Rapeseed-mustard requires 0.33 to 0.40% S in leaf for obtaining 90% of its potential yield (Cheema and Arora, 1984). Oilseeds (*Brassica* species/cultivars) vary in their sensitivity to sulphur deficiency and S requirement for optimum seed yield and quality (Malhi *et al*., 2005). Plant tissue should contain one part of S for every 15-20 parts of N for optimum growth and production. Its concentration varies among species and it ranges from 0.1-0.6 % of the dry matter (De Kok *et al*., 1997). Sulphur partitioning at various growth stages of Indian mustard shows that the maximum S concentration lies in the leaves (Fig. 1).

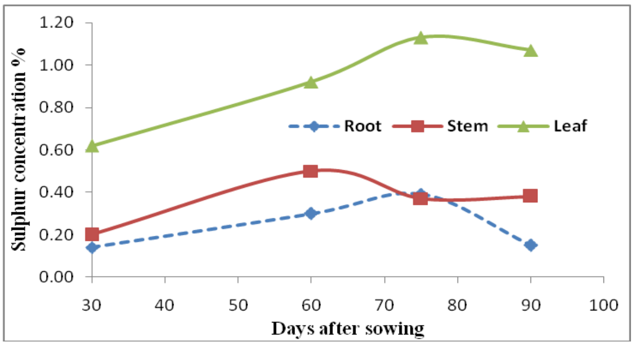


Fig 1: Sulphur content in Indian mustard

Plants contain a large variety of organic S compound, as thiol (glutathione) and secondary S compound (allins, glucosinolate, phytochelatine etc.) which play important role in the physiology and protection against environmental stress and pests (De Kok *et al*, 1998). Sulphur deficiency results in accumulation of amides and carbohydrates and in turn, retards the formation of chlorophyll and causes stunted plant growth and pale green coloration of young leaves.

Sulphur is an essential element in forming protein, enzyme, vitamins and chlorophyll in rapeseed-mustard like in other plants. Three S containing amino acids *viz*. methionine (21% S), cysteine (26% S) and cystine (27% S) are the building blocks of proteins. Out of the total plant S, about 90% is present in these amino acids (Tandon and Messick, 2002). Sulphur is also a constituent of plant hormones like thiamine and biotin, both of which are involved in carbohydrate metabolism. Cysteine is the precursor of glutathione, a water-soluble thiol compound which functions in the protection of plant against oxidative stress, heavy metal toxicity and xenobiotics. Sulphur helps in the synthesis of sulfhadryl protein, –SH group which helps the plant to tolerate dry and cold stress condition. Sulphur compounds are also of great importance for food and quality and for the production of phyto-pharmaceuticals. It activates certain enzyme systems and is a component of some vitamins (Vitamin A). Sulphur is found in mustard oil glycoside, which imparts characteristics odors and flavor to plants like mustard. Many plant species, particularly Brassicaceae crops, incorporate S into a wide range of secondary compounds such as the sulfation of flavonol, desulfoglucosinolate, choline, and gallic acid glucoside (Leustek and Saito, 1999). Several studies show that glucosinate levels in Brassicaceae vegetables will change in response to S and nitrogen fertilizer treatments (Aires *et al.*, 2006). Chhonkar and Shroti (2011) reported an increase in growth characters of mustard. Singh and Singh, 1983 reported enhancement of the chlorophyll synthesis in mustard, Sah *et al*. (2006) reported that all growth attributes increased significantly up to 40 kg S ha$^{-1}$. The results showed that the uptake of NPK and S by both seed and stover increased significantly with successive increase in N levels up to 120 kg N ha$^{-1}$ and S levels up to 60 kg S ha$^{-1}$ (Sah *et al*., 2006). Chlorophyll content in mustard increases with increasing levels of S up to 60 kg S/ha and linear regression was observed.

Yield attributes of Indian mustard increased significantly with increasing level of S up to 45 kg ha$^{-1}$ (Issa and Sharma 2007). The increase in yield attributes of mustard with increasing level of S may be ascribed to the role of S in improving mineral nutrition of the crop (Chauhan *et al*. 2002, Rana *et al*. 2005). Optimum seed and oil yield of mustard occurred at about 20 kg S ha$^{-1}$ (Zhao *et al*. 1994). The application of S at the rate of 100 kg ha$^{-1}$ increased S uptake by 10–15 kg ha$^{-1}$ and applications of N at a rate of 300 kg ha$^{-1}$ increased S uptake by 29–34 kg ha$^{-1}$ in double and single low varieties of oil seed rape. Deficiency of S results in severe yield losses to Indian mustard, due to its higher demand for the synthesis of protein, co-enzymes, S- containing amino acids and glucosinolates (De Kok et *al*., 2000). Sulphur starvation evokes alterations in the pools of several metabolites followed by disruption in nitrogen metabolism. In general, the S levels between 30-40 kg S ha$^{-1}$ enhanced the oil and seed yield of Indian mustard (Fig 3).

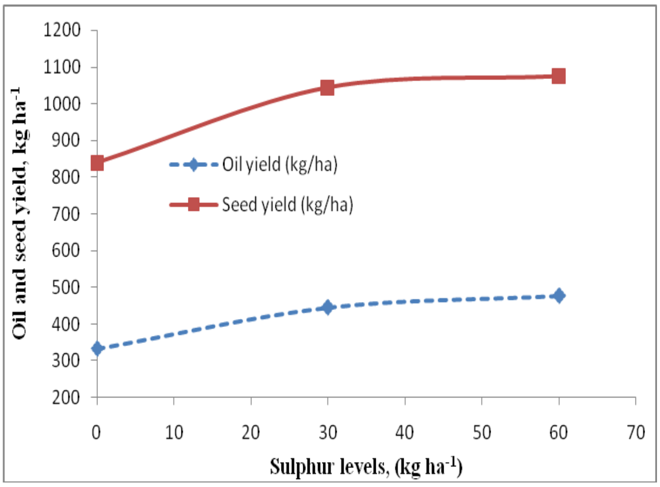



Fig3: Seed and oil yield of Indian mustard under different doses of Sulphur

A significant increase in yield was observed with increase in S levels up to 40 kg S ha$^{-1}$ in mustard based cropping system. In rice-mustard sequence, the optimum seed yield of mustard was obtained at 40 kg S ha$^{-1}$ at Behrampore and for blackgram-mustard at Dholi. Each successive increase in S level increased seed yield up to 20 kg S ha$^{-1}$ at Dholi and Ludhiana, 40 kg S ha$^{-1}$ at SK Nagar and 60 kg S ha$^{-1}$ at Behrampore and Morena conditions (AICRP-RM, 2008). The various sources of S also have impact on different yield attributes and yield. Application of bentonite S gave significantly higher growth, yield attributes, seed yield, than to gypsum and wettable S (Fig 4).

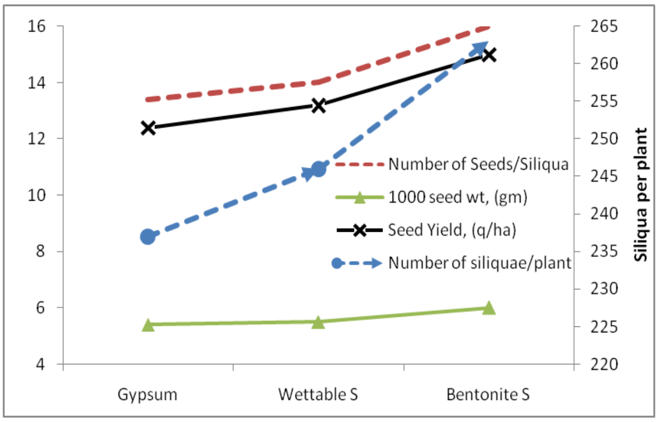



Fig 4: Response of Indian mustard to different S sources

Pandey *et al.* (2010) reported significant interaction between S levels with mustard genotypes with respect to grain yield (Table 1). Mustard variety Varuna and Kranti at 20 kg S ha$^{-1}$ produced significantly higher.grain yield than Pusa Bold at 30 kg S ha$^{-1}$. Similarly these varieties at 30 kg S ha$^{-1}$ level also produced significantly higher grain yield than Pusa bold at 40 kg S ha$^{-1}$.

Table 1: Effect of S levels on seed yield (kg ha$^{-1}$) of three mustard genotypes

| Levels of S (kg ha$^{-1}$) | Varieties | | |
|---|---|---|---|
| | Varuna | Kranti | Pusa Bold |
| 0 | 743.0 | 649.0 | 613.0 |
| 10 | 945.0 | 892.0 | 793.0 |
| 20 | 1077.0 | 1014.0 | 843.0 |
| 30 | 1143.0 | 1112.0 | 889.0 |
| 40 | 1178.0 | 1189.0 | 910.0 |
| CD (P=0.05) | | 175.0 | |

AICRP-RM (2009) reported highest seed yield of mustard under black gram-mustard cropping system with 60 kg S ha$^{-1}$ at Dholi (Fig 5). Pooled data for 6 years also revealed superiority of black gram-mustard sequence with application of 20 kg S ha$^{-1}$ over other treatments.

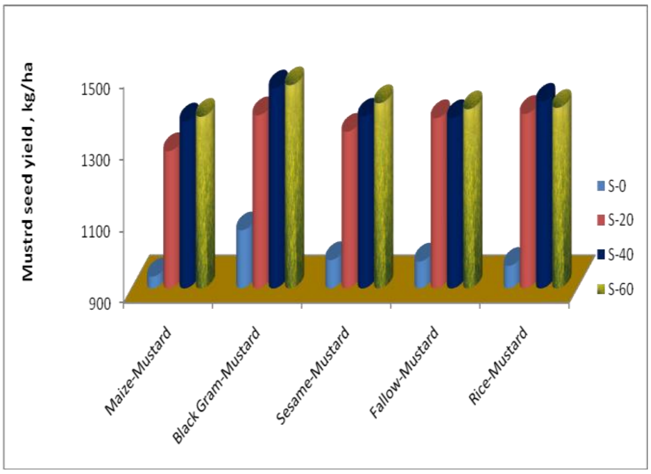


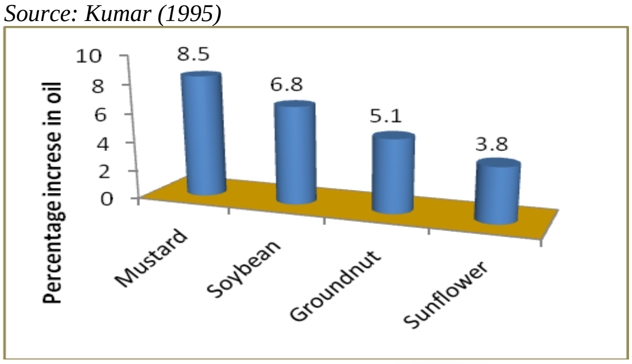

Fig. 5: Response of mustard under various cropping systems to sulphur levels

Sulphur application significantly increased the oil content in Indian mustard (Bhagat and Soni 2000; Saha and Mandal 2000; Chauhan *et al.*, 2002; AICRP-RM, 2003 and Shukla *et al.*, 2005; Rana *et al.*, 2005; Issa and Sharma 2007; Sardana *et al*, 2008; Degra 2008; Pandey *et al.*,2010; Nanjundan et al , 2011; Dash and Ghosh 2012). The increase in the oil content in the seeds of mustard is associated with the increase in acetyl-CoA carboxylase activity, which is also precursor for oil synthesis. Foremost, S is a constituent of methionine, the first amino acid required in the protein synthesis (acetyl-CoA carboxylase). Subsequently, S is associated to the proper functioning of nitrate reductase (Ahmad *et al.*, 1999), the enzyme regulating the flow of $NO_3^-$-N into the amino acids and subsequently into protein synthesis. Hence, the application of S influences oil accumulation in developing seeds of mustard by enhancing protein synthesis (Inayat *et al.*, 2010). Kumar (1995) and Pankaj et al (2010) reported linear correlation between the levels of S and protein and oil content in toria (M27). Interestingly, higher levels of S maintained maximum protein and oil content in toria, otherwise there is negative correlation between these two important characters (Table 2). Sulphate-S application was reported to increase oil in canola seed also (Malhi and Gill 2002; Malhi *et al.*, 2005).

Table 2: Effect of different doses of S on yield, oil content and protein content of toria

| Doses of S (kg ha$^{-1}$) | Protein content in seed (%) | Oil content (%) | Oil yield (kg ha$^{-1}$) | Seed yield (kg ha$^{-1}$) |
|---|---|---|---|---|
| 0 | 24.6 | 39.6 | 332.2 | 839 |
| 30 | 26.5 | 42.6 | 444.7 | 1044 |
| 60 | 27.6 | 44.3 | 476.6 | 1076 |
| CD (5%) | 1.1 | 1.2 | 29.9 | 66.0 |

*Source: Kumar (1995)*



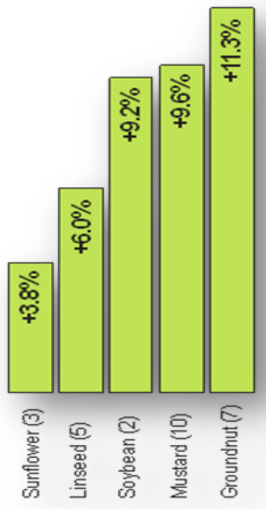




Fig 6: Increase in oil content of various oilseeds due to S application

Crops differ in their S requirement, absorption and their utilization capabilities within plant parts. Also, their capacity to mobilize native S reserves of the soil is different. Among all oilseed crops, maximum increase in oil content due to S application has been reported in Indian mustard (Fig 6). Relative susceptibility of oilseeds to S stress in general is in order of Raya> Mustard> Linseed> Sesame. Pankaj et al. (2010) also reported a reduction in eurecic acid in mustard with sulphur application. Not only oilseed crops, but their cultivars too vary in their yield potential and relative tolerance to S stress. Similarly, tolerance of mustard cultivars to stress were recorded in the order of Pusa Bold> Varuna> Gj-1. Magnitude of response varied from 26-35% over control S treatments. Oil content in Canola-4 and Hyola-401 is 3% higher than the hybrid 'PGSH-51' due to the effect of various doses of nitrogen and S, while the oleic acid content in these hybrids are double than 'PGSH-51'. 'PGSH-51' had erucic acid ranging from 23.2 and 29.4%. At higher S level there is 2-3% reduction in erucic acid content. Higher doses of S along with low doses of nitrogen affect the chain elongation enzyme system thereby leading to reduction in erucic synthesis (Table 3).

Table 3: Effect of N and S application on fatty acid composition and glucosinolate content in *Brassica juncea* cv. Varuna at Ludhiana

| N (kg ha$^{-1}$) | S (kgha$^{-1}$) | Glucosinolate (μ moles/g in defatted meal) | Palmitic acid | Stearic acid | Oleic acid | Linoleic acid | Linolenic acid | Eicosenoic acid | Erucic acid |
|---|---|---|---|---|---|---|---|---|---|
| 75 | 0 | 64 | 2.61 | 1.17 | 11.78 | 14.99 | 6.48 | 50.91 | 11.80 |
| 75 | 20 | 72 | 2.88 | 1.31 | 10.15 | 14.53 | 5.14 | 52.75 | 12.28 |
| 100 | 0 | 52 | 2.58 | 1.58 | 13.16 | 15.31 | 7.01 | 49.55 | 10.57 |
| 100 | 20 | 42 | 2.91 | 1.65 | 11.94 | 15.06 | 6.13 | 49.63 | 12.18 |
| 125 | 0 | 52 | 3.01 | 1.33 | 12.19 | 16.17 | 5.91 | 47.71 | 12.26 |
| 125 | 20 | 42 | 4.42 | 1.31 | 16.12 | 16.55 | 6.57 | 44.77 | 9.55 |

*Source: AICRP-RM (2007)*

**Sulphur as phytoremediator**

Sulphur is also an important element in diluting the harmful effect of heavy metal toxicity caused by cadmium. A complex is formed between S and cadmium, which is retained in the vacuoles as cell waste. The stability of the plastocyanin-cadmium complex is enhanced by additional S ions once the complex is in the vacuole (Oritz *et al.*, 1992). Sulfate salts increases cadmium uptake and tolerance by facilitating S uptake which enhances glutathione production which in turn increases plastocynin production, allowing the plant roots to complex more cadmium, reducing toxicity, and allowing more uptake of cadmium. High concentration of cadmium in the soil increases a toxin called malondialdehyde (MAD) content in both roots and shoots which results in dramatic reduction in growth parameters of the plant including plant height, root and shoot weight, tillers per plant, chlorophyll content and net photosynthetic rate. Increased S levels help to increase in growth parameters and a reduction in cadmium and MAD content. In addition super oxide dimutase (SOD) activity also reduces and glutathion content increases, indicating a positive effect of S in alleviating oxidative stress (Hassan *et al.*, 2005).

**Interactive effect of S with other nutrients**

The S uptake of the crop mostly depends upon the balance between the S and other nutrient element within the plant as well as soil. S has some synergistic and antagonistic effect with other nutrient elements. Since, N and S are both closely linked in protein metabolism, the interaction between N and S is reported to be synergistic. These two nutrients increased the concentration and uptake of each other in the plant. An antagonism between P and S has been established. However, several studies also reveal that there is a positive interaction between the two. The P and S interaction happened to be synergistic at low to medium level of P is maintained. Based on the results of three years of field experiments on mustard, maximum increase in oil yields was obtained at 75 kg ha$^{-1}$ N and 60 kg S ha$^{-1}$ S, which indicates a significant positive interaction between than. Adequate N: S ratio has been found to be 7.5:1 in grains, above which deficiency of S can be observed (Aulakh *et al*., 1980).

Adequate S must be applied to rapeseed-mustard for optimum nitrogen utilization. Sulphur is also required for utilization of P and other essential nutrients. Sulphur ranks equal to N for optimizing crop yields and quality. It increases the size and weight of seed crops and enhances the efficiency of N for protein manufacture. S is major nutrient factor influencing partitioning of P: S and nitrogen accumulation in plant especially the symbiosis nitrogen fixation in legumes (Dwiwedi *et al*., 2005).

The N and S relationships are very important in *oilseed Brassicas* (Jackson, 2000). The application of mineral S fertilizer dramatically increases seed yield and S uptake of oilseed rape (McNeill *et al*., 2005). Jackson (2000) investigated the four N rates in combination with three S rates and the results showed that the seed yield and oil content were closely related to available nitrogen. Oilseed crops, such as rape and mustard, are sensitive to S and/or K deficiency (Malhi *et al*., 2007). Oil content increases up to 46.6% with 45 kg S $ha^{-1}$ as compared to the oil content of 42.8% with no S. The K and S interaction on protein content of rape and mustard showed that when applied with the lowest level of S, oil content significantly increased with each increment in K level. In contrast, at highest level of S, oil content decreased significantly with each increment in K level. On the other hand, at 30 kg S $ha^{-1}$ rate, protein content increased when K level was increased to 60 kg K $ha^{-1}$ (Amanullah *et al*., 2011).

**Sulphur management in rapeseed-mustard**

**Rates of S application**

The rate of S application also varies depending upon the soil and crop needs but 20-50 kg S $ha^{-1}$ is generally recommended. The application rate should be correlated with both crop needs and S status in the soil (Table 4). The AICRP-RM trials on use of S for enhancement of quality and productivity revealed that 40 kg S $ha^{-1}$ increased seed yield and net return in different mustard based cropping sequences. Application of sulphate-S at about 15-30 kg S $ha^{-1}$ is usually sufficient to prevent S deficiency in canola on most of the S-deficient soils.

Table 4: S fertilizer recommendations based on available S status of soils

| Available S in soil (mg $kg^{-1}$) | S fertility class | Increase in yield (%) | Soil deficiency class | Amount of S fertilizer added (kg $ha^{-1}$) | | |
|---|---|---|---|---|---|---|
| | | | | Cereal | Oilseeds | Pulses |
| <5 | Very low | 25-85 | Very high | 60 | 40 | 30 |
| 5-10 | Low | 20-50 | High | 45 | 30 | 20 |
| 10-15 | Medium | 5-20 | Moderate | 30 | 20 | 15 |
| 15-20 | High | 1-5 | Low | 15 | 10 | 10 |
| >20 | Very high | 0 | Very low | 0 | 0 | 0 |

*Source: Patel et al. (2001)*

The trials under AICRP-RM have come out with many recommendations for the levels of S. Addition of S invariably in all types of soils in mustard along with zinc in zinc deficient soils was recommended during 1999-2000. In the cropping system mode for different zones, 40 kg S $ha^{-1}$ should be applied in different cropping sequences involving mustard (2000-01). The adoption of guar-taramira system was remunerative with 40 kg S $ha^{-1}$ over fallow–taramira sequence at Jobner and be adopted in semi-arid eastern plain zone of Rajasthan . Application of 40 Kg S $ha^{-1}$ to toria crop proved to be remunerative at Shillongani and be adopted in Assam (2001-02) in cluster bean-mustard sequence. In pearl millet- mustard sequence, application of 80 Kg N + 30 kg $P_2O_5$ $ha^{-1}$ along with 10 t FYM + 40 kg S + 25 kg $ZnSO_4$ in the mustard crop is recommended for southern parts of Haryana (2003-04). The S recommendation was also made as a part of INM as application of 10 t FYM $ha^{-1}$ + 40 kg S $ha^{-1}$ + 25 kg $ZnSO_4$ $ha^{-1}$ + 1 kg B $ha^{-1}$ + seed treatment with Azotobactor for obtaining higher and sustainable yield of mustard (1998-99). Application of RDF + 10 t FYM 40 kg S + 25 kg zinc sulphate + 1 kg boron $ha^{-1}$ (taramira) was found remunerative and can be adopted in semi-arid eastern plain zone of Rajasthan, particularly in soils having deficiency of these nutrients (2002-03) during 2004-2005, INM practices i.e RF + 2 t FYM (in seed furrows) + 40 kg S + 25 kg $ZnSO_4$ + 1 kg boron + Azotobector (seed treatment) is recommended for getting higher seed yield of mustard in zone V (Shillonganil) over recommended fertility level and 2 t FYM $ha^{-1}$ (in furrows) + 40 kg S $ha^{-1}$ (through gypsum) over 75% of recommended fertility was found more remunerative in moong-mustard cropping sequence and is recommended for North Gujarat condition. At SK Nagar, Gujarat application of 40 Kg S through gypsum was found remunerative at for North Gujrat areas and spray of thiourea (0.1%) at flower initiation along with basal application of 40 Kg S $ha^{-1}$ through gypsum could be done in North – Western Part of Rajasthan during 2003-04.

Degra *et al.*, (2008) found significant increase in yield attributes and seed yield and significantly highest net returns, B: C ratio (2.5:1) of mustard up to 60 Kg S $ha^{-1}$ at Durgapura, Rajasthan. At Bawal and Morena, highest seed yield 2060 kg $ha^{-1}$ was obtained with 40 kg (S $ha^{-1}$) + thiourea (0.1%). At Sriganganagar, significantly higher seed yield (1883 kg ha$^{-1}$) was recorded at 40 kg S ha$^{-1}$+thiourea (0.05%), urea (2%), $H_2SO_4$ (0.1%) and 40 kg S ha$^{-1}$. The highest oil content (35.9%) was recorded with thiourea 0.1% spray. Glucosinolate content ranged from 115-154 (µ mole/g defatted meal) in different treatment (Table 7). Sulphur increased the yield of mustard by 12 to 48% under irrigation, and by 17 to 124% under rainfed conditions.

**Method and time of application**

In order to increase the S use efficiency, it is not only necessary to apply the correct amount (on soil test basis) in a balanced proportion with other limiting nutrient element in the soil, but it is equally important to apply it at the proper physiological stage of the plant. Since, S is leachable, like nitrate, it is safer to apply close to the time of plant uptake by splitting the doses. This is especially true for sandy soils. Band application is recommended, but broadcasting also works well if adequate rainfall or irrigation is available to leach the S into the root zone. Side-banding is the most effective way to apply sulphate-S fertilizers to produce maximum seed yield and to prevent any damage to mustard seedlings. In relatively moist areas, broadcast-incorporation methods can produce seed yield similar to side-banding in most years (Malhi, et *al.*, 2005). The S mineralizaiton rate is highest for crucifers (57- 85% of the total S added) and lowest for legume (up to 46% of total S added). Only limited amounts of sulphate S fertilizer can be safely applied near the seed. Application of sulphate-S to mustard at seeding time gives the highest increase in yield and S uptake (Malhi *et al.*, 2005).

The best yield response to sulphate S fertilizer was at 30 kg S ha$^{-1}$ either incorporated or side banded before sowing, as illustrated (Fig7). Applications at sowing are generally more effective than at early flowering stages.

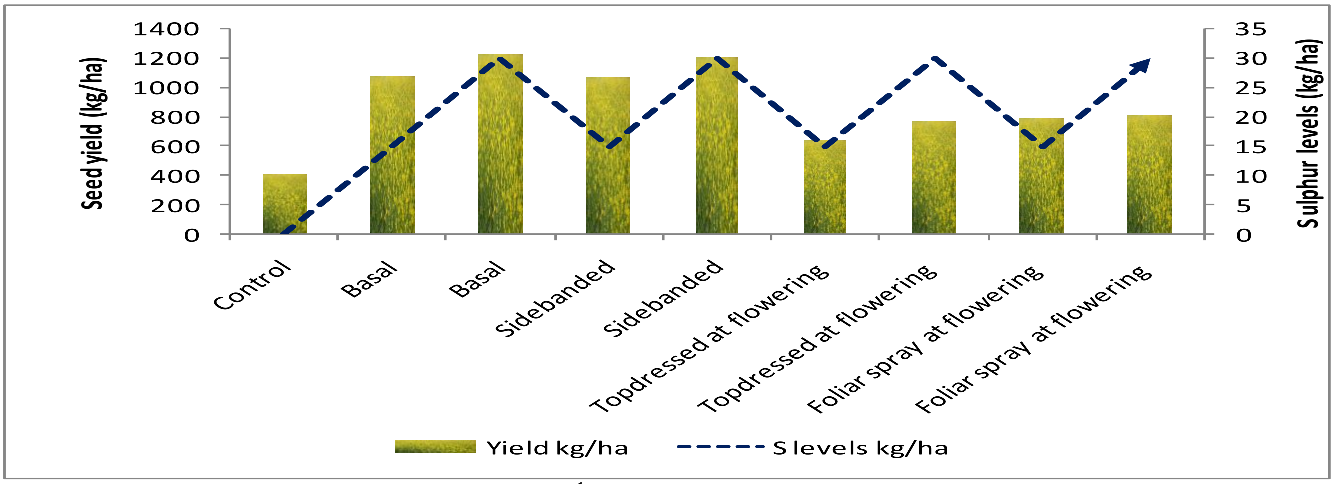



Fig. 7: Increase in seed yield (kg ha$^{-1}$) under different methods and levels of S fertilizers

Application of sulphate-S at bolting can significantly restore seed yield, while an application at early flowering can moderately correct S deficiency damage (Malhi, *et al*, 2005). Sulphur is less mobile than nitrogen within the plant parts. Since, S requirement of the crop is more at early growth stage, its application should be made prior to bud initiation or flowering to ensure better crop yields. However, on the basis of critical value of S in plants, application of S fertilizers should be done (Table 5). Deficiency of S in rapeseed-mustard could be determined by plant tissue test for total. But, the S provided by this method may be late to cure the S deficiency and restore seed yield of the current crop to optimum levels. The ratio of hydriodic acid reducible (HI-S): total S in plants at the rosette stage was found to be the most accurate index of status of S in plants, and a ratio of less than 0.38 may reduce seed yield due to S deficiency in canola plants (Maynard *et al*. 1983). If the N: S ratio is more than 15:1, S fertilization should be done. Histuda *et al.*, (2005) demonstrated that tolerance to low externals (<2.0 mg L$^{-1}$) and the critical tissue S levels for S deficiency varied significantly among species tested of oilseed *Brassica*.

Table 5: Critical levels of S in selected 45-55 days old crop plants

| Crop | S concentration in dry matter (%) | | |
|---|---|---|---|
| | Deficient | Moderately sufficient | Sufficient |
| Mustard, groundnut, soybean, cowpea, French bean | 0.10-0.25 | 0.25-0.45 | >0.45 |

In case, if the S application is missed at sowing, S may be top dressed to 20-40 days of growth to get good yield. The foliar spray of S is less effective as compared to its soil application because of the high S requirement of the crop. The trials under AICRP-RM, 2003 revealed better results of foliar spray of thiourea at flowering and basal placement of S before sowing (Table 6). If S deficiency symptoms appear on foliage, 3-5 sprays of 0.5% soluble sulfate salts like ammonium sulfate, potassium sulfate, zinc sulfate etc. can be done on the standing crop.

Table 6: Seed yield, net returns, and quality of mustard as influenced by foliar application of S sources

| Treatment | S.K.Nagar | | Sriganganagar | Ludhiana | | |
|---|---|---|---|---|---|---|
| | Seed yield (kg ha$^{-1}$) | Net returns over control | Seed yield (kg ha$^{-1}$) | Oil content (%) | Oil yield (kg ha$^{-1}$) | Glucosinolate (µ mole/g defatted meal) |
| Control | 1707 | - | 1604 | 34.7 | 375 | 130 |
| Thiourea (0.1%) | 2087 | 3226 | 1696 | 35.9 | 429 | 142 |
| 40 kg S ha$^{-1}$ | 2249 | 6712 | 1799 | 35.2 | 405 | 149 |
| 40 kg S ha$^{-1}$ + Thiourea (0.1%) | 2039 | 4070 | 1883 | 33.4 | 411 | 134 |
| $ZnSO_4$ (0.5%) | 1921 | 4622 | 1667 | 33.2 | 372 | 126 |
| CD at 5% | 150 | - | 158 | - | - | - |

*Source: AICRP-RM, 2003*

**Sources of sulphur**

As the S containing fertilizers are expensive and therefore their efficient and judicious use should be made to incur higher benefits. The selection of S fertilizers commonly used for correction of deficiency in different soils and crops depend upon their cost and easy accessibility. Strategies for efficient management of S fertilizers are listed in Table 7.

Table 7: Sulphur carrying fertilizers and their management in different crops

| S No. | Fertilizer | S content (%) | Management |
|---|---|---|---|
| 1 | Ammonium sulfate | 24 | Integrated N+S application, particularly for topdressing |
| 2 | Single super phosphate | 16 | Integrated P+S application for basal dose. |
| 3 | Potassium sulfate | 18 | Integrated K+S application for chloride sensitive crops |
| 5 | Elemental S | 85 | For fine textured calcareous soil. Application 3-4 weeks before planting in soil |
| 6 | Pyrite | 22 | Suitable for alkaline soil. Surface application before planting |
| 7 | Gypsum | 18 | For crops requiring high calcium |
| 8 | Zinc sulfate | 15 | Depending upon the zinc needs of the crop |

Sardana, (2008) reported an increase in seed yield of 8.9% with foliar application of thiourea @ 0.05% at flower initiation to 22.2% with soil application of 20 kg S/ha as gypsum at sowing+ foliar application of thiourea @ 0.05% over control. Net returns and B: C ratio were higher with basal application of 20 kg S ha$^{-1}$ through gypsum + foliar application of thiourea (0.05%) closely followed by spray of 0.15% Sic acid and soil application of gypsum to supply 40 kg S ha$^{-1}$. When pyrite is used as a source of S, it should be broadcasted as fine powder on soil surface under moist condition 7-10 days before sowing to ensure high conversion of unavailable S to plant available form. Application of bentonite S gave significantly higher growth, yield attributes, seed yield, oil yield, nutrients (NPS) uptake, net return , B: C ratio, production, economic and water use efficiency, than to gypsum and wettable S (Tetarwal *et al*., 2013). A variety of S-bentonite fertilizers have been produced to improve the effectiveness of granular elemental S. Particles of S-bentonite are sized for blending with solid N, P and K fertilizers. When it is applied to soil, this bentonite component imbibes soil moisture, causing fertilizer granules to disintegrate into finely divided S, which is more rapidly converted to $SO_4^{2-}$. Nibedita et al., 2009 reported maximum increase in seed and oil yield (Fig 8) of rapeseed (*Brassica campestris L.*) due to spray of 0.15 and 0.2 % nitrosulf (a liquid formulation with 33 % S).

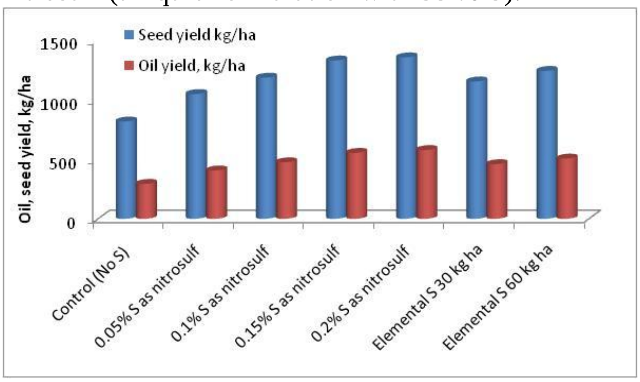



Fig 8: Effect of liquid and elemental S on seed and oil yield of rapeseed

Das and Ghosh (2012) observed maximum increase in seed yield due to magnesium sulphate at every level (Table 8). The maximum seed yield was obtained with 40 kg S ha$^{-1}$ applied as magnesium sulphate. Further, better response was reported with $MgSO_4$ over gypsum at 40 and 60 kg S ha$^{-1}$ to Indian mustard, an increase in seed yield was 14.3-22.5 %.

**Table 8: Effect of sources and levels of S on seed yield of mustard**

| Source of S | S levels (kg ha$^{-1}$) | Seed yield (kg ha$^{-1}$) | % increase over control |
|---|---|---|---|
| Gypsum | 20 | 1705 | 14.3 |
| Magnisium sulphate | 20 | 1777 | 19.1 |
| Gypsum | 40 | 1799 | 20.6 |
| Magnisium sulphate | 40 | 1828 | 22.5 |
| Gypsum | 60 | 1782 | 19.4 |
| Magnisium sulphate | 60 | 1806 | 21.0 |
| Control | 0 | 1492 | - |

**Fortified S fertilizers**

Elemental S can be readily incorporated into N/P fertilizer materials to provide 5% to 20% S. Monoammonium and diammonium phosphates (MAP or DAP) containing from about 5 to 20% S can be made. S in granulated triple superphosphate (TSP) and DAP fertilizers oxidizes faster than S alone in both acid and calcareous soils. This S-enriched SSP has received attention in the area with high leaching losses of plant nutrients because of its potential for reducing $SO_4^{2-}$ leaching loss and also providing available $SO_4^{2-}$ to meet crop needs during the whole growing season.

**Sulphur Coated Fertilizers**

S coated urea (SCU) is a controlled release N fertilizer consisting of an S shell around each urea particle. It contains 77% to 82% of urea (36% to 38% N) and 14% to 20% S coating.S coated urea has the greatest potential for use in situations where multiple applications of soluble N sources are needed Although S in the coating may not be sufficiently available to correct deficiencies during the early season of the first year after application, it will become an important source of plant available S in the latter growing season and succeeding year.S coating may also be used to intentionally supply plant nutrient S.

**Liquid S Fertilizers**

Low water solubility hampers the use of mainstream sulphate fertilizers such as ammonium sulphate and potassium sulphate. Hence the liquid or suspension S fertilizer formulations have gained importance. Ammonium thiosulphate solution (ATS) is a 60% aqueous solution with 12-0-0-26S analysis. Potassium thiosulphate (0-0-25-17S) and calcium thiosulphate solution is suited as a starter fertilizer for crops and situations requiring these other nutrients besides S. They are clear liquid fertilizers which are suitable for direct applications or blending, offers versatility to farmers and fertilizer retailers.

**Integrated use of S with organic manure**

Organic bound S is the potential source of plant available S in many soils. Therefore, use of organic manure improves the availability of S in soils and leaves residual effect for longer time. Application of 20 (kg S ha$^{-1}$) + 5 t FYM to a crop carries significant residual effect for the succeeding crop and it also increases utilization efficiency of native S. Integrated effect of pyrite in combination with 10 t ha$^{-1}$ of FYM or pressmud results in significant increase in yield than their alone application.Catch crop may help to avoid S deficiency and increase synchrony between plant demand and available soil S in the crop rotation. Though they can't fulfill the need of S demanding crops, but they can make important supplement as nutrient source. Catch crop might reduce sulfate leaching and therefore increase the overall S use efficiency in crop rotation. Although all crops including leguminous, ryegrass etc. are beneficial, the best catch crop (legume on sandy soil), sequester 10-12 kg S ha$^{-1}$ and poorest catch crop sequester < 3.0 kg S ha$^{-1}$ (Erickson *et al*., 2000).

**Conclusion**

Sulphur is now known as the fourth major plant nutrient, along with N, P, and K. High yield of good quality produce becomes possible only when crops have access to optimum amount of S. Sulphur is a component of three main amino acids namely; cysteine, cystein and methionine, hence essential for protein synthesis. Presently the gap between the removal and addition of the S is 0.5 million tonnes of available S and it is likely to widen to further 2 million tonnes by the year 2025. S is the cheapest nutrient out of four major nutrients required by the crops (N, P, K and S). Its application is less expensive but gives high profits than other nutrients. Sulphur deficiency from Indian soils can only be eliminated by the proper management of S in crops. Application of S not only helps in sustaining high yields but also improves quality of the produce of rapeseed-mustard. Mustard responds well to S levels of 40-60 kg/ha through SSP, gypsum, or betonite S. The oil in rapeseed-mustard could increases by 3-9%. This is important in Indian context as the country is short of vegetable oils and is importing a sizable amount of foreign exchange every year. For obtaining the best-desired results from S application to the deficient soils, proper measures should be taken to improve the effectiveness of the S fertilizers. Strategies need to be developed to encourage more use of S through judicious mix of fertilizer S, byproduct S, and organic manure attaining sustainable high mustard productivity.

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