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Review Paper

Role of Sulphur nutrition in oilseed crop production - A review

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Abstract

Sulphur is an essential nutrient for the production of oilseeds. It is the 13*th* most abundant element in the earth's crust with an average concentration of 0.06 percent. It is necessary for the synthesis of proteins, oils, and vitamins. Agricultural soils have a low concentration of inorganic sulfur compared to the organic form. A sulfur deficiency also leads to a 40 percent reduction in the quality and quantity of rapeseed or oilseeds. Sulfur deficiency is becoming very common in many states of India. In previous years, various studies on sulfur have been carried out, viz. factors that affect the availability of Sulphur to plants, its function in the plant, the response of Sulphur in various crops, etc. The objective of this review is to provide an update on recent discoveries related to these topics, which may contribute to a better understanding of S fertilization and the role of S in oilseeds.

***Key words** :Deficiency, sulphur, oilseeds*

Introduction

Sulfur is an essential nutrient for the production of oilseeds. It is the 13th most abundant element in the earth's crust with an average concentration of 0.06 percent. Sulfur (S) is increasingly recognized as the fourth major plant nutrient after nitrogen, phosphorus, and potassium (Jamal *et al*., 2010). Oilseeds of one hectare remove sulfur about 10 to 25 kg and that of legumes 5 to 10 kg per year, depending on the crop, soil and environmental factors (Singh and Singh, 2016). In India, more than 41 percent of the soils are deficient in Sulphur (Singh, 2001). Since rapeseed has a high demand for sulfur, it is particularly sensitive to sulfur deficiency compared to other crops such as cereals or legumes (Zhao *et al.,* 1997). The visual symptoms of sulfur deficiency in cruciferous crops are very specific and can be treated in the field throughout the growing season (Pierre *et al.,* 1999). During flowering, the characteristic changes in sulfur deficiency in the color and shape of the petals (Haneklaus *et al.,* 1999). A deficiency of sulfur leads to an accumulation of amino acids, which is supposed to regulate the absorption and assimilation of nitrogen, while the processes which increase the renewal of organic sulfur, the compounds of defense against stress and answers are shields. Severe deficiency, sulfur can ultimately lead to reduced growth, which is particularly associated with a reduced epidemic rate (Hawkesford and De Kok, 2006). Sulfur deficiency also leads to a 40 percent reduction in the quality and quantity of rapeseed or oilseeds (De Pascale *et al.,* 2008).

Sulphur deficient oilseeds growing soils of India

In coarse-textured soils, where the oilseeds cultivation is mainly done, total sulphur content is low than the fine-textured soils. Low content of organic matter in coarse-textured soils result in sulphur deficiency (Takkar, 1988). Major oilseed growing states in India are Gujarat, Andhra Pradesh, MP, Maharashtra, Tamil Nadu, Karnataka U.P., Rajasthan, Orissa, and Punjab, etc (Table1). 40.7 per cent S-deficient soil samples from various part of the country (Singh, 1991) were reported by ICAR based on their project on micronutrient in which S was included. Out of total S, only 10 percent proportion is in available form but it varies from soil to soil. Organic S is the major source of available S for crop uptake. 10 ppm available is the critical limits, below which the soils are stated to be deficient in S (Venkatesh and Satyanarayana, 1999)

N:S and S:P ratio

N:S Ratio of about 20:1 is required for the optimum growth of plants (Cram, 1990). Accumulation of non-protein compounds such as amides occurs, when sulphur is deficient leading to a greater N:S ratio. Apart from it, when S supply is greater than that required for protein synthesis, sulphate accumulates in plant tissues, leading to a smaller N:S ratio. S concentration of 0.2 percent and an N:S of 18 in the flag leaf is sufficient for obtaining higher yields in wheat (Reneau *et al.*, 1986). Availability or deficiency of

Table 1: Percentage of deficient sulphur samples in different districts of states collected by ICAR (TSI 2020)

Punjab	
Over 40%	Amritsar, Hoshiarpur, Ludhiana and Ropar
20% - 40%	Sangrur and Kapurthala
Less than 20%	Ferozepur, Faridkot, Bathinda and Patiala
Bihar and Jharkhand	
Over 40%	Laxmipur, Navada, Ranchi and Singhbhum
20% - 40%	Samastipur, Gopalganj, Gaya, Patna, Darbhanga, Nalanda, Aurangabad, W. Champaran, Bhojpur, Palamau, Dumka and Rohtas
Less than 20%	Muzaffarpur, Bhagalpur, Jehanabad and Munger
Madhya Pradesh and Chhatisgarh	
Over 40%	Dewas, Ujjain, Mandsaur, Dhar, Morena, Vidisha, Rajnandgaon, Gwalior, Sehore, Indore, Sidhi, Chhindwara, Balaghat, Seoni and Khandwa
20% - 40%	Bhopal, Jabalpur, Bhind, Guna, Satna, Sagar, Ratlam and Raipur
Less than 20%	Narsinghpur, Bilaspur, Durg, Mandla and Betul
Rajasthan	
Over 40%	Banswara, Dholpur, Chittorgarh
20% - 40%	Bharatpur, Sriganganagar, Bikaner, Udaipur, Jhunjhunu and Kota
Less than 20%	Jaipur, Jodhpur and Nagaur
Uttar Pardesh and Uttaranchal	
Over 40%	Lucknow, Banda, Ballia, Hardoi, Varanasi, Pratapagarh, Faizabad, Kanpur, Gazipur, Mirzapur
20% - 40%	Allahabad, Sitapur, Hamirpur, Jhansi, Lalitpur, Bulandshahr, Agra, Fatehabad, Firozabad, Mainpuri, Aligarh, Moradabad
Less than 20%	Jalaun, Farukhabad, Nainital, Almora, Gaziabad, Meerut
Haryana	
Over 40%	Ambala, Faridabad and Hisar
20% - 40%	Gurgaon, Jind, Panipat, Sonepat, Mohindergarh, Bhiwani and Kaithal
Less than 20%	Rohtak, Reawari, Sirsa and Kurukshetra

S in protein is determined by the N:S ratio. N and S ratio is generally preferred as a diagnostic criterion for S deficiency (Spencer and Freney, 1980). However, Schnug and Hanklaus (2000) reported that the use of the N:S ratio as a diagnostic criterion is not optimum as the same ratio of N:S can be obtained at totally different concentration levels in the tissue. Similarly, optimum S:P ratio is also of great consideration regarding crop growth which falls between 0.9-1.4 (Abdin *et al.,* 2003).

Deficiency symptoms of sulphur in oilseeds

Sulphur deficiency results in the production of pale green, yellowish-green or solid yellow. Symptoms of Sulphur deficiency look like Nitrogen (N) but appear first in younger leaves due to less mobility in the plant than N, while in the case of nitrogen, they appear first in the older leaves. The S stored in older leaves in the form of sulfate is easily mobilized and transferred to the growing organ to some extent. However, this type of sulfur is not enough to maintain normal growth, therefore the young leaves remain small and pale green due to a lack of protein and chlorophyll. Disruption of protein metabolism in the synthesis of chloroplasts and chlorophyll leads to acute deficiency. Cell division is also reduced due to an S deficiency which causes the plant to atrophy (Schnug and Haneklaus, 2005).

Interaction of Sulphur with other nutrients

Positive interaction of nitrogen (N) and sulphur was reported in the case of mustard (Sachdev and Dev, 1990). Similarly, P and S interaction is reported to be positive in sunflower (Gangwar and Parmeswaran, 1976) and mustard (Raut and Ali, 1985) on a low level of phosphorus (P). However, at a high level of P, negative interaction was reported in the case of groundnut and lentil crop (Tiwari, 1990). Potassium (K) and S interaction was also positive for groundnut (Singh and Chaudhari 1996).

Uptake of Molybdenum (Mo) was reduced with sulphur application (Chaphale *et al.,* 1991). The antagonistic effect was recorded for molybdenum with increasing levels of sulphur (Guyette *et al.,* 1989). Mo, when added with S, improved growth parameters due to their effectiveness as well as their effect on an increase in nitrogen and sulphur uptake (Sairam *et al.,* 1995). However, in wheat crops, Magnesium (Mg) uptake was increased in wheat when Mo was applied either alone or with sulphur (Purakayastha and Nad, 1998).

In the case of Iron (Fe) and S, the combined application of both nutrients showed an increase in plant growth (Malewar and Ismail, 1997). Sulphur antagonism with Selenium is well known. S uptake in the plants decreases with an increase in selenium use (Pezzarossa *et al.,* 1999). Synergistic as well as antagonistic relationship was found between boron and sulphur in various studies (Singh, 2000). Similar results were also recorded in the case of zinc in which antagonistic and synergistic effects of Zn and S interaction have been reported. Higher S dose lowered Zn concentration in groundnut was described by Shukla and Prasad, (1979) and in rice by Shah and De Datta, (1991) also reported that Zn concentration in rice plants was slightly decreased with an application of 100 kg S ha^{-1}. On the other hand, Cui and Wang (2005) in spring wheat and Baudh and Prasad, (2012) in mustard reported a positive interaction between zinc and sulphur.

Inorganic and Organic Sulphur

Agricultural soils have inorganic sulphur in low concentration as compared to organic form (Kumar *et al.,* 2018). In the case of inorganic S, sulphate can be categorized into SO_4^{2} in soil solution, adsorbed SO_4^{2} and mineral sulphur (Barber, 1995). Sulphur may form a precipitate with calcium, magnesium or sodium sulphate. SO_4^{2} also occurs as a co-crystallized or co-precipitated impurity with $CaCO_3$ which forms an important fraction of it in calcareous soils (Tisdale *et al.,* 1993). However, soil organic sulphur constitutes up to 98% of the total soil sulphur (Bloem, 1998) and it is associated with soil organic matter and soil microorganisms (Freney, 1986).

Availability of indigenous sulphur sources

Gypsum: Gypsum is widely used for many years as a soil conditioner, it also contains a considerable amount of Ca and S. Gypsum is a cost-effective and efficient source of sulphur. It is extracted from mines and sulphur reserves in-country accounts for 1,004 million tones out of it, 90 percent of the total reserves are located mainly in Jodhpur, Nagaur and Bikaner districts of Rajsthan (Rohtagi *et al.,* 1977). Rajasthan State Mines and Mineral Ltd. (RSMM) and the Fertilizer Corporation of India (FCI) are major producers of mineral gypsum in India. Bio-products of gypsum which nowadays in use are phospho-gypsum can be manufactured through the wet process by treating rock phosphate with sulphuric acid.

Pyrites: The main constituent of pyrites (FeS_2) minerals are iron and sulphur. In some places of Bihar, Rajasthan, and Karnataka, deposits of them occur. Generally, pyrites categorized into low and high-grade ones. Sulphur acid is produced through the use of high-grade pyrites, in which low-grade pyrites are not of much industrial importance. However, low-grade ones can be used for increasing soil fertility as a source of sulphur (Awasthi and Shaha, 1998).

Immobilization and mineralization of sulphur

Sulphur cycle involves two major processes *i.e.,* mineralization and immobilization. Both S immobilization and mineralization are mediated primarily by microbial activity in soil (Knights *et al.,* 2001). Importantly, the rate at which added sulphate is immobilized depends critically on soil conditions (Ghani *et al.,* 1993). As stated earlier, organic matter is the main source of S in soil (Lucheta and Lambais, 2012). Oxidation of it to SO_4^{-2} is done by microorganisms and the process is called mineralization. Mineralization can be influenced by various factors like aeration, moisture, soil pH and temperature. The availability of oxygen is a major factor affecting the oxidation process. Oxidation process leads to the formation of SO_4^{-2} and H^+ ions which also leads to low pH in soil (Kumar *et al.,* 2018). However, under low sulphur supply and excess carbonaceous material, the available sulphur gets used by microorganisms and leads to immobilization of sulphur. On the other hand, immobilization is a temporary process and sulphur again mineralized on the death of microbes (Kumar *et al.,* 2018). Sulphur is largely related to carbon present in the soil, therefore proper C:S is required rather than the availability of soil organic carbon. Optimum temperature conditions for the transformation process falls between 35-40 ÚC. While moisture at 60 percent of the field capacity ensures proper oxidation (Lucheta and Lambais 2012). Mobility and fate of sulphate in soils helps to evaluate the degree of mineralization and immobilization. Several studies showed that a highly mobilized pool of sulphur is that which is recently get immobilized. Immobilized sulphur is converted by microbial action into C-bonded S (Castellano and Dick, 1991). Both these reports represent field studies, whereas in a laboratory study it was reported that for recently immobilized S both sulphate ester and C-bonded S were rapidly mineralized (Ghani *et al.,*1993). Soils with different plant species also influenced sulphur transformation, this is mainly due to the rhizosphere effect rather than purely plant type. Some microbes play an important role in sulphur transformation as compare to other microbes but the study of such microorganisms is still under investigation (Rappe and Giovannoni, 2003).

Reduction-oxidation reactions of sulphur

Reduction-oxidation reactions of sulphur are generally controlled by autotrophic bacteria *Thiobacillus*. Beijerinck (1904) isolated the *Thiobacillus denitrificans* (S-oxidizing bacteria) and *Thiobacillus thioparus*. Similarly, Lipman *et al.* (1916) also reported the oxidation capacity of soil samples (sterilized and non sterilized) treated with sulphur. In 2000, Genus *Thiobacillus* was reclassified into 17 species which was dependent on the sequence of the 16S r RNA gene and DNA-DNA hybridization (Kelly and Wood, 2000). New genera (*Acidithiobacillus*, *Halothiobacillus*, and *Thermithiobacillus*) is proposed in the new classification (Robertson and Kuenen, 2006).

The presence of *T. thiooxidans* varies in soils of different nations. In majority, soils in Australia and New Zealand have a sufficient population of *T. thiooxidans* (Vitolins and Swaby, 1969; Lee *et al.,* 1987) whereas in Canada, its population was not detected (Lawrence and Germida, 1991). Under conditions when the availability of air is low, SO_4^{-2} is reduced and used by *Desulphovibrio* and change into sulfites and sulfides (Kumar *et al.,* 2018). In the case of excess aeration, oxidation is solely a chemical process, while oxidation dominantly occurs through biochemical way.

Physiology of sulphur nutrition in oilseeds

The importance of sulphur as a plant nutrient has been recognized since the middle of the last century. Plants meet their S requirements for soil, air, irrigation water and the application of pesticides containing S. Proper supply of S to plants can increase crop yield and quality of oils. Sulfur represents 0.1 to 0.5 percent by dry weight in oilseeds where it is present in both organic and inorganic compounds. Sulfate absorption is slightly lower than phosphate. S is absorbed mainly by plants from sulfate-shaped roots (SO_4), but it can also be absorbed by leaves in the form of SO_2 gas from the atmosphere. However, this S gas must be transformed into sulfate. After absorption, the sulfate is transported to the endoderm where it is secreted in the xylem and transported to the leaf by the flow of perspiration. In chloroplast, sulfate is reduced first to sulfide and then incorporated into cysteine. Much of the cysteine S is transferred to methionine and most of these two are incorporated into proteins, where cysteine is responsible for the secondary structure. Sulfide that is not incorporated into proteins is converted into sulfate and stored in the leaves and, to a lesser extent, in the seeds and can be mobilized when necessary. S is necessary for the synthesis of proteins, oils, and vitamins. About 90 per cent of the reduced S is required for the protein because it is constitutive of methionine (21 per cent S), cysteine (26 per cent S), cystine (27 percent S). About 50 percent of the total sulfur content of proteins is found in methionine. S is also a component of the S-glycosides in mustard oil, coenzyme A, the biotin and thiamine vitamins and the ferredoxins in which cysteine S is incorporated. Cystine is formed by the oxidation of two cysteine molecules. The iron and sulfur protein centers serve as electron carriers. S compounds and volatile volatile sulfides are the source of spice onions (Mengel and Kirkby, 1987).

Role of sulphur in Oilseeds
a) Yield improvement

Sulfur plays a predominant role in improving the quality of sunflower seeds as well as in the efficient use of nitrogen and phosphorus. Sulfur helps in the synthesis of cysteine, methionine, chlorophyll, vitamins (B, biotin and thiamine), carbohydrate metabolism, oil content, protein content and also associated with growth and metabolism, in particular for its effect on enzymes protolytics (Najar *et al.,* 2011). Kumar and Trivedi (2012) have also reported an increase in mustard seed yield with the application of S levels. With an increasing supply of sulfur, the process of tissue differentiation from somatic meristematic to reproductive and developmental activity primordial flower could have grown, resulting in more flowers and siliqua, a longer siliqua and a higher seed yield. Rapeseed (*Brassica rapa* L.), an important oil crop, has a high demand for S (Fismes *et al.,* 2000). Due to its high S requirements, the use of 30 and 60 kg ha^{-1} of S fertilizer has been recommended for maximum yield. Varenyiova *et al.* (2017) reported that the highest yield of 3.96 t ha^{-1} was achieved with the application of 40 kg of sulfur ha^{-1}. An average oil content of 45.1, 45.5 and 44.0 percent were based on treatments in which doses of sulfur fertilizers of 15, 40 and 65 kg ha^{-1} were applied. The higher yield and oil content with a greater application of sulfur have also attributed the synthesis of proteins and enzymes, as it is a component of sulfur-containing amino acids, namely methionine, cysteine , and cystine (Kumar *et al.,* 2011). Sulfur plays an imperative role in the formation of sesame seeds and is also responsible for the proper functioning of the plant system and a general increase in the parameters of sesame growth and yield (Mab *et al.,* 2012). Minz *et al.* (2017) conducted a pot experiment to analyze the effect of sulfur nutrition on growth, yield, nutrient absorption, and oil content of flax crops at Kanpur. The results revealed that the height of the plant (66.13 cm), no. branches per plant (6.35), test weight (8.60 g), seed yield (14.33 g per pot) and stem yield (20.75 g per pot) were higher with 40 ppm sulfur application. The oil content (40.85 percent) was higher for an application of 60 ppm of sulfur, 4.53percent more compared to the control (39.08%). Khatkar *et al.* (2009) launched a field study during the 2004-2005 winter season at the Allahabad agricultural research farm to assess the effect of nitrogen, phosphorous, and sulfur fertilization on the growth and yield of mustard (*Brassica juncea*). Plant attributes such as plant height, pods per plant, seeds per pod, pod length, and seed yield were improved with each successive dose of sulfur application.

b) Quality improvement

In oilseeds crops like groundnut, rapeseed-mustard, etc., applications of sulphur along with other nutrients significantly increased the oil content (15-30 percent) (Ahmad *et al.,* 1999). Application of sulphur speed up the process of protein synthesis in the plant (Ahmad and Abdin, 2000). The composition of oil, acetyl-CoA and acetyl-CoA carboxylase in oilseeds also get effected through sulphur nutrition. The proportion of different fatty acids in some oilseeds determines its use such as high linolenic acid in linseed oil is beneficial for the quality manufacturing of paints etc. In addition to it, sulphur application accelerates linolenic acid synthesis and result in a lower quantity of stearic, oleic and linoleic (Ahmad *et al.,* 2000). Sulphur plays an important role in specialized peptides, such as glutathione and thioredoxins, in redox reactions.

The most important factor in the quality of rapeseed is its oil content, which is directly proportional to its protein content (Brennan *et al.,* 2000). The protein content correlates negatively with the oil content, so the effect of sulfur on the oil content of winter rapeseed is ambiguous (Krauze and Bowszys, 2000). The quality parameters studied, namely. Crude protein content and oil content and yield increased with increasing levels of S. (Raja *et al.,* 2007). S application increased the cysteine, methionine and cysteine contents of soybean by 52,117 and 58 percent, respectively (Kumar *et al.,* 1981). Similarly, 68 and 23 percent increase of cystine and methionine, respectively in sunflower was recorded by Badiger *et al.,* (1982). In rapeseed and mustard the S caused an increase of 16, 9 and 20 percent increase of Cystine, methionine, and cysteine, respectively (Somani *et al.,* 1988). The proteins accumulated in oilseed seeds that contain a high level of S amino acids are of great importance in feeds used to feed livestock. Such a type of protein with a high level of amino acids containing S could also be used by humans as a vegetable protein (Von Der Haar *et al.,* 2014). In addition, antioxidant, antidiabetic, anorectic, anticancer and antiviral activities have been reported for rapeseed protein peptides (Wanasundara, 2011; Aachary and Thiyam, 2012). Malhi *et al.* (2007) conducted a field experiment during 2003, 2004 and 2005 on a S-deficient Gray Luvisol (Boralf) soil near Star City, in northeastern Saskatchewan to study effect of sulphur application on different Brassica oilseed species/cultivars. They concluded that there was a significant increase in protein content in seed as compared to straw. Ahmad *et al.* (2007) performed an experiment at Cereal Crops Research Institute, Pirsabak, Nowshera, Pakistan to find out the influence of nitrogen and sulfur on canola (*Brassica napus* L. cv. Bulbul-98). They observed that glucosinolate content escalate from 13.6 to 24.6 µmol/g with hike in S application from 0 to 30 kg/ha. Similarly, protein content also improved from 22.4 to 23.2 percent as S rate was increased from 0 to 20 kg/ha.

Sulphur application alone or in combination with boron also resulted in improved protein as well as oil content in soybean as illustrated by Longkumer *et al.,* (2017). They found that fertilization of Sulphur @40 kg/ha and B@1.5 kg/ha resulted 28 percent increase in protein and 33 percent increase in oil content as compared to control. Similarly, sulphur and boron nutrition effect on soybean was studied in a three year experiment. In a nutshell, results revealed that the optimum levels of sulphur and boron (30kg sulphur per hectare and 1.5 kg boron per hectare) were found to be best for obtaining maximum yield attributes, yield, oil and protein content, total uptake of sulphur and boron (Devi *et al.,* 2012).

A pot experiment which is comprised of four different sources of sulphur (Cosawet sulphur, Gypsum, Bentonite sulphur and Elemental sulphur) and five levels of sulphur (0, 5, 10, 15, and 20 ppm) combinations was carried out by Sisodiya *et al.* (2016) and they stated that protein content was increased with increase in sulphur doses but interaction between levels and sources of sulphur was non-significant.

Conclusion

In India, the productivity of oilseeds remains low due to the low consumption of S fertilizers and a large propagation deficit. The sulfur requirements of oilseeds can be met by a number of S-containing materials, such as gypsum, phosphogypsum, S elements, pyrite and iron sulfate. It can also be added with fertilizers containing primary nutrients such as ammonium sulfate, SSP, potassium sulfate, etc.

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