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A Critical Review on Sulphur Application in Rapeseed-mustard to Enhancing Productivity and Oil Quality

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Authors' contributions

This work was carried out in collaboration among all authors. Author MKM wrote the initial draft. Authors AS and PB contributed extensively to the conceptualization and development of the manuscript. All authors contributed to the writing, editing, and revision of the final manuscript. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

Sulfur (S) plays a vital role in determining the seed yield, oil content, quality, and resistance to various stresses in rapeseed-mustard. It is essential for chlorophyll formation, oil synthesis, seed protein, amino acids, enzymes, and glucosinolate in these plants. Sulphur also boosts mustard

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seed production. However, due to modern agricultural practices, including multiple cropping, the use of sulfur-free fertilizers, and limited organic manure application, soil sulfur levels are depleting rapidly in India. Indian soils typically contain between 10 to 6319 mg kg-1 of sulfur, with most agricultural soils averaging 30 to 300 mg kg^{-1}. Adding sulfur increases mustard oil content by enhancing the activity of an enzyme called acetyl-CoA carboxylase, which is essential for oil synthesis. Sulfur also mitigates the harmful effects of heavy metal toxicity, especially from cadmium. Sulfur interacts with other nutrients in both positive and negative ways. Recommendations for sulfur fertilization in different mustard growing regions have been made based on various research programs. To maximize sulfur use efficiency, it's crucial to apply the correct amount based on soil tests and in balance with other limiting nutrients. Timing of sulfur application is also important; it's best applied at the beginning but can also be top-dressed 20-40 days after planting for optimal yield. Research suggests that mustard responds well to foliar spraying of thiourea during flowering and basal placement before sowing. This paper reviews the strategies to improve sulfur utilization through advancements in application rates, methods, and sulfur sources on rapeseed-mustard.

Keywords: Amino acid; sulphur source; calcareous soil; cost benefit ratio; bentonite.

1. INTRODUCTION

Rapeseed (*Brassica napus* L.) is a significant oilseed crop, ranking second only to sunflower [47]. It contains seeds with a protein content ranging from 28 to 36%, making it highly nutritious. This crop is typically grown in the winter (*Rabi*) season and thrives in cool temperatures, requiring adequate soil moisture during its growth phase and a dry period for harvesting. Rapeseed can be cultivated under both irrigated (79.2%) and rainfed (20.8%) conditions, and it prefers well-drained sandy loam soil [44]. It has relatively low water requirements, making it suitable for rainfed cropping systems, with about 20% of the total area allocated for rainfed cultivation. Varieties within the rapeseed-mustard group include brown sarson, raya, and *toria* crops [42, 45].

To increase and stabilize rapeseed-mustard productivity and production, it is crucial to effectively manage natural resources, adopt integrated approaches to plant-water, nutrient, and pest management, and expand cultivation to new areas under various cropping systems [1,2]. Essential nutrients like nitrogen, phosphorus, and sulfur play pivotal roles in enhancing yield and quality. Sulfur, in particular, is essential for increasing oil content and yield [31,21]. Its application significantly affects processes like chlorophyll synthesis, carbohydrate metabolism, and protein synthesis. Sulfur is vital for amino acid and protein production, oil synthesis, vitamin A components, and enzyme activation in plants [24,29,39]. Amino acids such as methionine, cysteine, and cystine, which are essential for protein synthesis, contain sulfur [18,8]. In oilseeds, sulfur also contributes to the formation of chlorophyll, glucosides, glucosinolates (responsible for mustard oil pungency), and sulphydryl linkages [15,17].

Adequate sulfur is critical for oilseed crops, and rapeseed-mustard has the highest sulfur requirement among oilseed crops [36,25,38]. Sulfur application can boost mustard yields by 12% to 48% under irrigated conditions and by 17% to 124% under rainfed conditions[4]. Piri and Sharma [19] observed that both seed and straw yields showed a substantial and statistically significant increase as the sulfur application rate increased, reaching the maximum benefit at the highest level of 45 kg S ha^{-1}. Jat et al. [7] similarly documented that the straw yield of Indian mustard exhibited an upward trend as the sulfur application level increased. Intensive agricultural practices, high-yielding crop varieties, multiple cropping, and the use of sulfur-free fertilizers have led to sulfur deficiencies in arable lands. The ratio of nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), and sulfur (S) in fertilizers has become imbalanced in favor of N, P_2O_5, and K_2O, with S lagging behind.

To address this issue, advanced techniques for sustainable sulfur management are urgently needed to bring the N: P_2O_5:K_2O: S ratio to desired levels. Currently, the average productivity of rapeseed-mustard in India is only 1145 kg per hectare, and there is a goal to increase it to 2562 kg per hectare by 2030 to ensure self-reliance in edible oil production [14]. Achieving this target will likely require comprehensive sulfur management practices to enhance oilseed productivity, particularly in the case of rapeseed-mustard, through precise sulfur-containing fertilizers to rectify deficiencies.

2. SULPHUR IN THE SOIL

Organic sulfur compounds make up a significant portion, up to 95-98%, of the total sulfur content in soil [34]. This organic sulfur is a diverse mixture derived from plant residues, animal matter, and soil microorganisms. Sulfur in soil exhibits similar behaviors and reactions as nitrogen [32]. It is a mobile nutrient and can move swiftly through the soil, especially in sandy surface layers. Sulfate, a common form of sulfur, carries a negative charge and is prone to leaching. Soluble sulfates rarely accumulate in the uppermost soil layer (up to 30 cm) as they tend to leach down into the B-horizon. Instead, sulfur often accumulates in the subsoil, where soluble sulfur interacts with iron and aluminum oxides. The accumulation of sulfur increases as subsoil acidity levels rise.Sulfur is released from organic matter and converted into sulfate through a process called mineralization [51]. The rate of mineralization depends on the ratio of carbon to sulfur (C:S), with a critical range of 200-300:1. When the C:S ratio is less than 200:1, there is net mineralization, and when it exceeds 300:1, net immobilization occurs. Soil microbes can immobilize sulfate if the organic residue contains a low amount of sulfur. Additionally, under waterlogged conditions, sulfate can volatilize as hydrogen sulfide (H_2S).

Sulfur deficiency is a common issue in many types of soils across India [40,52]. Soils in the Indo-Gangetic plains, red soils, lateritic soils, and hill soils are often prone to sulfur deficiency, while coastal soils typically have sufficient sulfur content. Calcareous soils, as well as medium and shallow black clay soils with low organic matter, are also susceptible to sulfur deficiency. In contrast, saline soils and acid sulfate soils in areas like the Sundarbans in West Bengal and coastal Kerala contain excessive amounts of sulfur in the form of sulfide or soluble sulfate, which can harm plants. As a result, there is significant variability in the total sulfur content in soils across different states of the country [46].Sulfur deficiency is more likely to occur in coarse-textured soils with low organic matter, in regions with high rainfall, in crop rotations that include pulses and oilseeds, in areas where sulfur-free fertilizers are frequently used, and in locations far from industrial activities that emit sulfur-containing gases [33]. Detecting sulfur deficiency in soil is not straightforward, but a combination of factors can be considered in a holistic approach to diagnose it. Just as there are indicators of sulfur deficiency in plants, certain indicators in soil can help identify sulfur deficiency [50].

3. IMPORTANCE OF SULPHUR IN RAPESEED-MUSTARD

Sulfur plays a specific and essential role in the growth of oilseed crops, particularly in the case of rapeseed-mustard. To achieve 90% of its potential yield, rapeseed-mustard plants need their leaves to contain approximately 0.33% to 0.40% sulfur content [9]. However, the sensitivity to sulfur deficiency and the specific sulfur requirements for optimal seed yield and quality can vary among different oilseed varieties and *Brassica* species [26].

For ideal growth and production, it is recommended that plant tissues should have a sulfur-to-nitrogen ratio of approximately 1:15 to 1:20. The actual concentration of sulfur in plant tissues can vary depending on the plant species and typically ranges from 0.3% to 7.6% of the dry matter [11]. When examining the distribution of sulfur in various growth stages of Indian mustard, it is evident that the highest sulfur concentration is found in the leaves (Fig. 1).

Plants contain a wide array of organic sulfur compounds such as thiol (like glutathione) and secondary sulfur compounds (including allins, glucosinolate, and phytochelatins), which serve important roles in their physiology and offer protection against environmental stress and pests [12]. When sulfur is deficient in plants, it leads to the accumulation of amides and carbohydrates. Consequently, this hinders the formation of chlorophyll, resulting in stunted plant growth and the development of pale green leaves in young plants [41].

Sulfur is indispensable for the formation of proteins, enzymes, vitamins, and chlorophyll in rapeseed-mustard, as well as in other plants. Three sulfur-containing amino acids, namely methionine (comprising 21% sulfur), cysteine (containing 26% sulfur), and cystine (with 27% sulfur), serve as the fundamental building blocks for proteins [22]. Remarkably, about 90% of the total sulfur in plants is found in these amino acids [49].

Sulfur also plays a role in the composition of plant hormones like thiamine and biotin, both of which are involved in carbohydrate metabolism. Cysteine serves as the precursor for glutathione, a water-soluble thiol compound that functions in protecting plants against oxidative stress, heavy metal toxicity, and harmful environmental substances. Sulfur contributes to the synthesis of sulfhydryl proteins (those containing -SH groups), which help plants withstand dry and cold stress conditions. Sulfur compounds have significant implications for food quality and the production of phyto-pharmaceuticals. Sulfur activates specific enzyme systems and is a component of certain vitamins, including Vitamin A. In plants like mustard, sulfur is found in mustard oil glycosides, which impart distinct odors and flavors to these plants. Many plant species, particularly those in the Brassicaceae family, utilize sulfur in the synthesis of various secondary compounds, such as flavonolsulfation, desulfoglucosinolates, choline, and gallic acid glucosides [23]. Several studies have shown that levels of glucosinates in Brassicaceae vegetables can change in response to sulfur and nitrogen fertilizer applications [3].

Research by Chhonkar and Shroti [10] demonstrated improved growth characteristics in mustard plants with increased sulfur levels. Yadav et al [43] reported enhanced chlorophyll synthesis in mustard, while Sah *et al*. [35] found that various growth attributes increased significantly up to 40 kg of sulfur per hectare. Their results indicated that the uptake of nitrogen, phosphorus, potassium, and sulfur by both seed and plant stover increased significantly with increasing levels of nitrogen (up to 120 kg N per hectare) and sulfur (up to 60 kg S per hectare) [35]. Furthermore, mustard chlorophyll content increased proportionally with higher sulfur levels, up to 60 kg S per hectare, as indicated by linear regression.

4. SULPHUR MANAGEMENT IN RAPESEED-MUSTARD

4.1 Application rate of S

The appropriate rate of sulfur (S) application can vary based on specific soil and crop requirements, but generally, a recommended range is between 20 to 50 kg of sulfur per hectare. It is crucial to determine the application rate by considering both the needs of the crop and the sulfur content in the soil (Table 1).

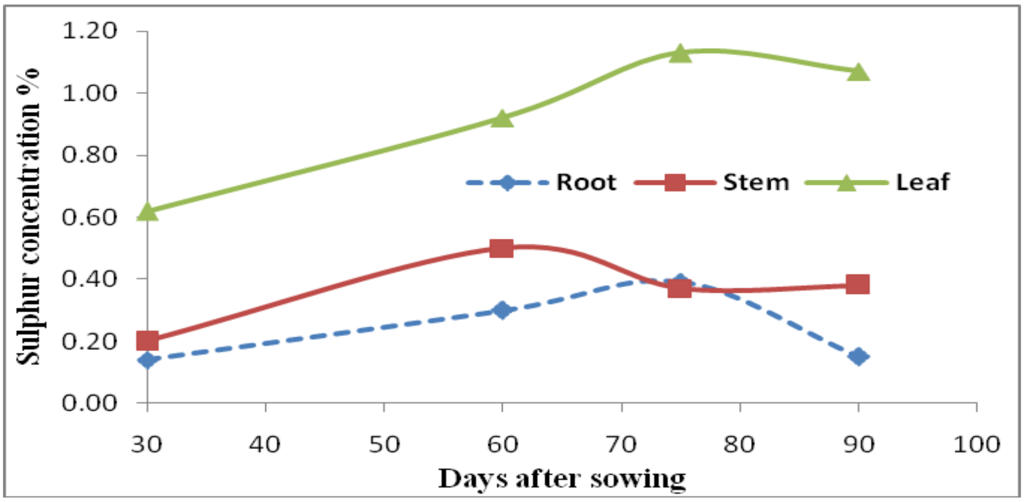

Fig.1. Sulphur content in Indian mustard [34]

Table1. S fertilizer recommendations based on available S status of soils [34]

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	Verylow	25-85	Veryhigh	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	Veryhigh	0	Verylow	0	0	0

Trials conducted by the AICRP-RM (All India Coordinated Research Project on Rapeseed-Mustard) regarding the use of sulfur to improve quality and productivity have shown that applying 40 kg of sulfur per hectare can enhance seed yield and net returns in various cropping sequences centered around mustard. Typically, for canola and similar crops, applying sulfate-S at a rate of approximately 15-30 kg of sulfur per hectare is generally sufficient to prevent sulfur deficiency, especially on soils that are deficient in sulfur.

Trials conducted across various agro-climatic regions have generated several recommendations regarding sulfur (S) levels for mustard cultivation. It is generally advised to add S to mustard crops, along with zinc and boron in cases where these nutrients are deficient in the soil. Mathpal et al. [27] for instance, observed significant improvements in the growth, yield, and yield-related characteristics of mustard when applying 60 kg/ha of sulfur compared to control, 15 kg/ha, and 30 kg/ha in Phagwara, Punjab.In a similar vein, Dogra et al. [13] reported significant increases in yield-related attributes, seed yield, and notably, the highest net returns with a benefit-to-cost ratio of 2.5:1 in mustard when sulfur was applied up to 60 kg/ha in Durgapura, Rajasthan. Kumar et al. [22] conducted research on mustard cultivation in Bhagalpur, Bihar, India. They assessed the yield response to different sulfur doses and sources and determined that the optimal sulfur dose was approximately 49.6 kg/ha when using bentonite as the source of sulfur. This was followed by 53.4 kg/ha for iron pyrite and 57.1 kg/ha for gypsum as sulfur sources (Fig. 2).

In various cropping systems adapted to different regions, it is recommended to apply 40 kg of sulfur per hectare when mustard is part of the sequence. Research conducted by the AICRP-RM has shown that adopting the guar-taramira system with 40 kg of sulfur per hectare was financially beneficial compared to a fallow-taramira sequence in the Jobner region, particularly in the semi-arid eastern plain zone of Rajasthan. Similarly, in the Shillongani area, applying 40 kg of sulfur per hectare to toria crops proved to be economically advantageous and is recommended for adoption, particularly in Assam (2001-02) when it's included in a cluster bean-mustard sequence.

For the southern parts of Haryana (2003-04) in a pearl millet-mustard sequence, the recommendation is to apply 80 kg of nitrogen, 30 kg of phosphorus, and 10 t of farmyard manure per hectare, along with 40 kg of sulfur and 25 kg of zinc sulfate in the mustard crop.Sulfur deficiency can lead to significant yield losses in Indian mustard due to its high demand for sulfur in the synthesis of proteins, co-enzymes, sulfur-containing amino acids, and glucosinolates [12]. When sulfur levels are maintained between 30-40 kg per hectare, it has been observed to enhance both oil and seed yields in Indian mustard (Fig. 3).

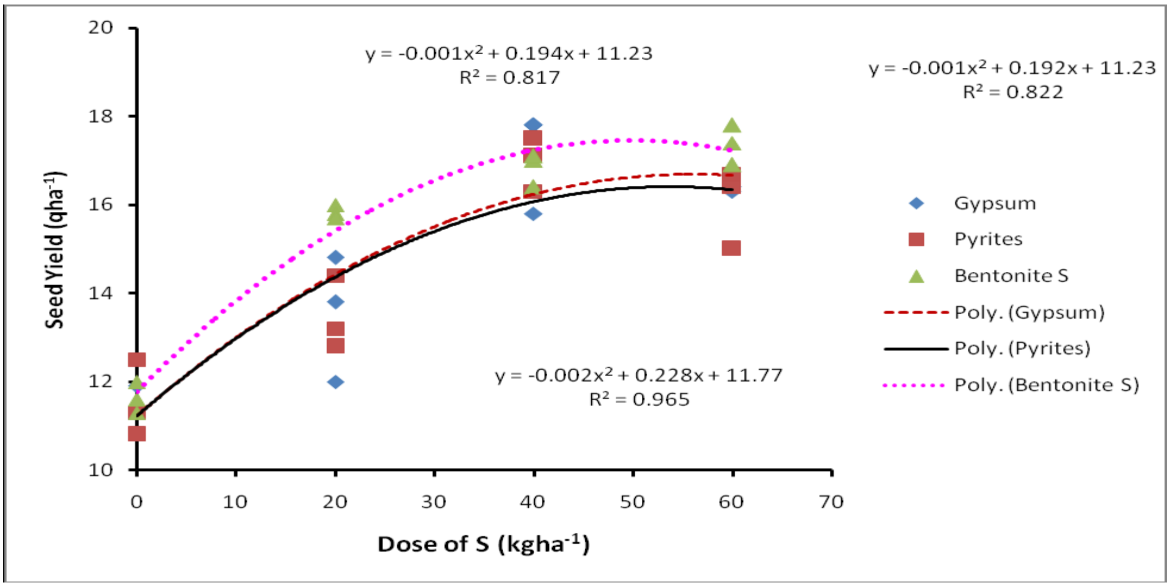

Fig. 2. Yield response equation as influenced by sources and doses of sulphur [22]

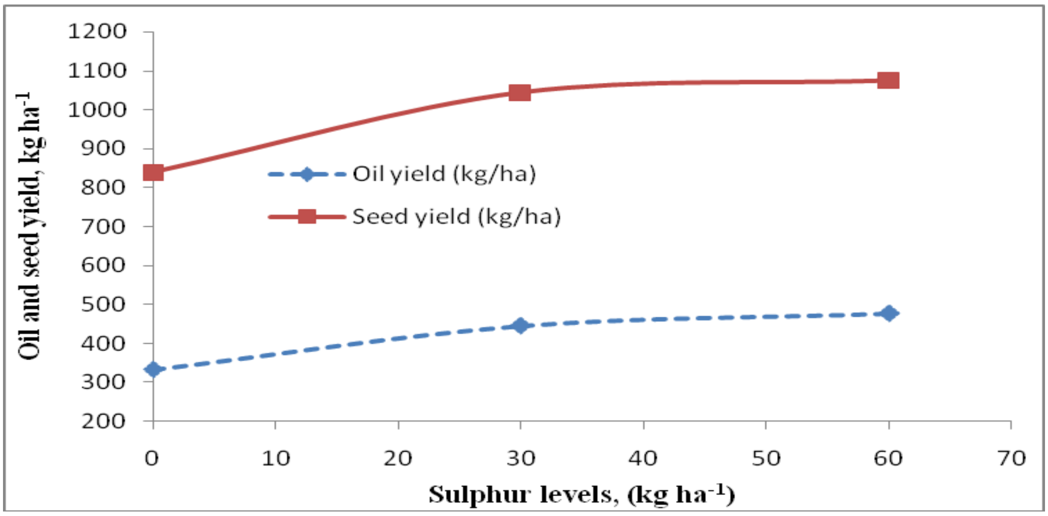

Fig. 3. Seed and oil yield of Indian mustard under different doses of Sulphur [34]

4.2 Application Method and Time

To enhance sulfur (S) use efficiency, it is crucial not only to apply the correct amount based on soil testing but also to maintain a balanced proportion with other limiting nutrients in the soil. Equally important is the timing of S application during the plant's physiological stages. Since sulfur is leachable, similar to nitrate, it's safer to apply it close to the time when the plant can uptake it, preferably by splitting the doses. This approach is especially critical for sandy soils. While band application is recommended, broadcasting can also work effectively if there is sufficient rainfall or irrigation to leach the sulfur into the root zone. Side-banding is considered the most effective method for applying sulfate-S fertilizers to maximize seed yield and avoid damage to mustard seedlings. In relatively moist areas, broadcast-incorporation methods can yield seed quantities similar to side-banding in most years [26].

The rate of sulfur mineralization varies among different crops, with crucifers exhibiting the highest mineralization rate (57-85% of the total added sulfur) and legumes having a lower rate (up to 46% of total added sulfur). Only limited amounts of sulfate-S fertilizer should be applied near the seed to prevent potential damage. Application of sulfate-S to mustard at seeding time results in the highest increase in yield and sulfur uptake [26]. The most favorable yield response to sulfate-S fertilizer is typically observed at a rate of 30 kg sulfur per hectare, whether it is incorporated into the soil or side-banded before sowing, as shown in Fig. 4.

Applications at sowing are generally more effective than those at early flowering stages. Applying sulfate-S at the bolting stage can significantly help restore seed yield, while applying it at early flowering stages can moderately alleviate damage caused by sulfur deficiency [26]. Sulfur is less mobile within plant tissues compared to nitrogen. Since the crop's sulfur requirement is higher during its early growth stages, sulfur application should ideally occur before bud initiation or flowering to ensure better crop yields. If sulfur application is missed at sowing, top dressing with sulfur can be done 20-40 days after growth initiation to achieve a good yield. Foliar spraying of sulfur is generally less effective than soil application due to the crop's high sulfur demand. Trials conducted under the AICRP-RM in 2003 showed better results with foliar spraying of thiourea at flowering and basal placement of sulfur before sowing.

4.3 Sulphur Sources

Because sulfur-based fertilizers can be costly, it is crucial to employ them efficiently and wisely to optimize their advantages. The selection of sulfur fertilizers for rectifying deficiencies in various soils and crops is often guided by considerations like cost and availability. Strategies for the efficient handling of sulfur fertilizers are detailed in Table 2.

In research by Kumar et al. [20] an increase in yield-related characteristics and seed yield was observed when using recommended dose of fertilizer (RDF) along with 40 kg of sulfur per hectare through single super phosphate. Sardana et al. [37] reported an increase in seed yield ranging from 8.9% with foliar application of thiourea at 0.05% during flower initiation to 22.2% with soil application of 20 kg of sulfur per hectare as gypsum at sowing, combined with foliar application of thiourea at 0.05%, compared to the control. Higher net returns and benefit-to-cost ratios were achieved with basal application of 20 kg of sulfur per hectare using gypsum, along with foliar application of thiourea at 0.05%. This approach was closely followed by the application of 0.15% Sic acid through spraying and soil application of gypsum to supply 40 kg of sulfur per hectare.

In the study by Biswas et al. [6] the maximum increase in seed yield and oil percentage was achieved with the application of 60 kg of sulfur per hectare in the form of single super phosphate (SSP). Nibedita et al. [48] reported that the highest increase in seed and oil yield for rapeseed (*Brassica campestris* L.) occurred due to the application of 0.15% and 0.2% nitrosulf (a liquid formulation containing 33% sulfur) through spraying (Fig. 5).

5. INTERACTION WITH ORGANIC MATTER

The utilization of organic manure can enhance the availability of sulfur in soils, as organic-bound sulfur serves as a potential source of plant-accessible sulfur in many soil types. This practice also leaves a lasting residual effect. For example, the application of 20 kg of sulfur per hectare along with 5 tons of farmyard manure (FYM) to a crop not only has a significant impact on the current crop but also benefits the succeeding crop by increasing the utilization efficiency of native sulfur. Combining pyrite with 10 tons per hectare of FYM or pressmud has been shown to result in a substantial increase in yield compared to applying these amendments individually.

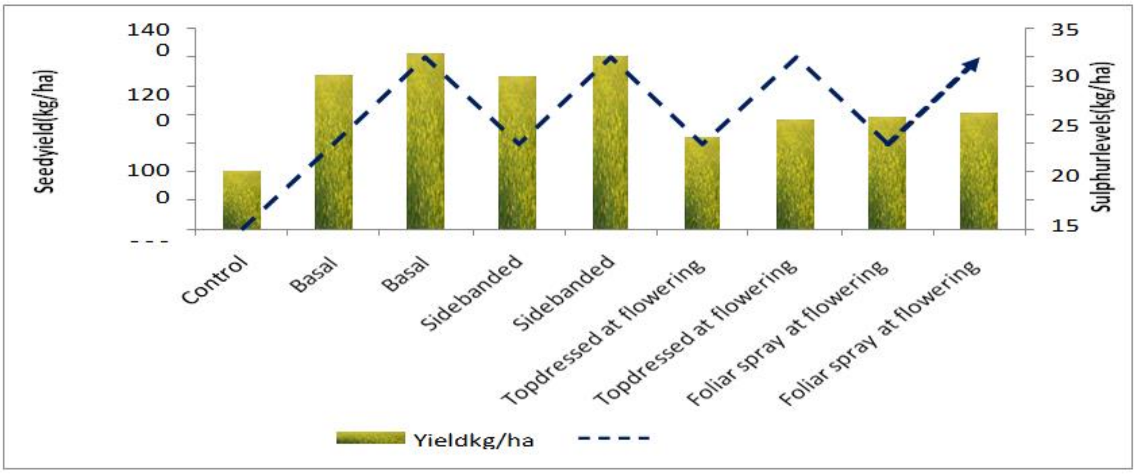

Fig. 4. Increase in seed yield (kg ha^{-1}) under different methods and levels of S fertilizers [34]

Table 2. Sulphur carrying fertilizers and their management in different crops [34]

S. No.	Fertilizer	S content (%)
1.	Ammonium sulfate	24
2.	Single superphosphate	16
3.	Potassium sulfate	18
4.	Elemental S	85
5.	Pyrite	22
6.	Gypsum	18
7.	Zinc sulfate	15

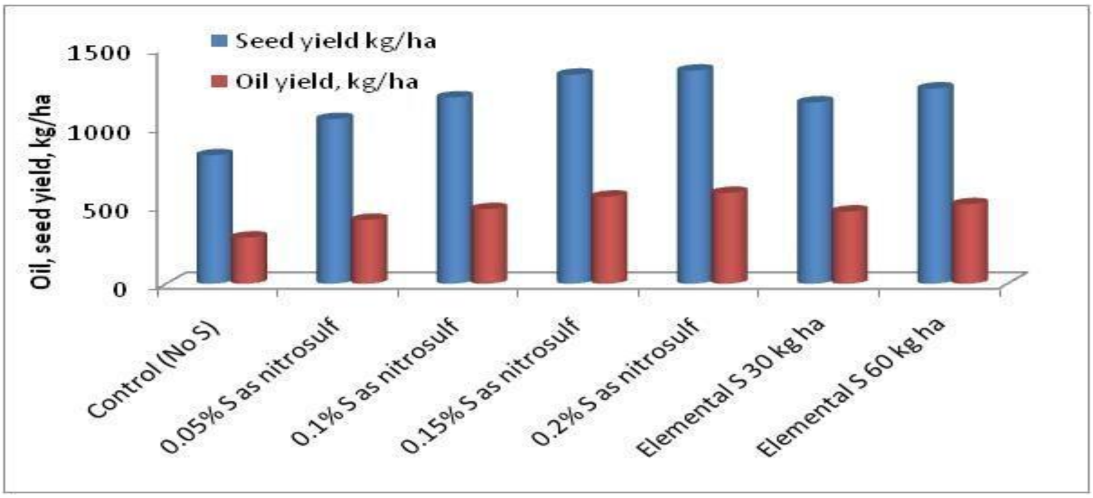

Fig. 5. Effect of liquid and elemental S on seed and oil yield of rapeseed [34,48]

Incorporating catch crops into crop rotation can help prevent sulfur deficiency and better align plant demand with the available soil sulfur. While catch crops may not fully meet the sulfur needs of sulfur-demanding crops, they can serve as important supplementary nutrient sources. Additionally, catch crops can reduce sulfate leaching, thereby enhancing overall sulfur use efficiency in crop rotations. Various catch crops, including leguminous and ryegrass species, provide benefits. Legumes, especially when grown on sandy soils, can sequester around 10-12 kg of sulfur per hectare, whereas less effective catch crops may sequester less than 3.0 kg of sulfur per hectare [16].

6. EFFECT OF S WITH OTHER NUTRIENTS

The uptake of sulfur (S) by crops is significantly influenced by the balance between sulfur and other nutrient elements present in both the plant and the soil. Sulfur exhibits both synergistic and antagonistic effects with other nutrients. For instance, because both nitrogen (N) and sulfur are closely linked in protein metabolism, their interaction is reported to be synergistic, meaning they enhance the concentration and uptake of each other within the plant [34]. On the other hand, an antagonistic relationship exists between phosphorus (P) and sulfur, although some studies have also shown a positive interaction between them. The P and S interaction tends to be synergistic when P levels are maintained at low to medium levels.

Based on the results of three years of field experiments with mustard, it was observed that the maximum increase in oil yields occurred at an application rate of 75 kg/ha for nitrogen and 60 kg/ha for sulfur. This finding indicates a significant positive interaction between these two nutrients. It has been found that a balanced N-to-S ratio of 3.1:1 in grains is essential, as sulfur deficiency can become evident when this ratio exceeds that value [5].To achieve optimal nitrogen utilization, it is necessary to apply sufficient sulfur to rapeseed-mustard crops. Sulfur is also required for the efficient utilization of phosphorus and other essential nutrients. Sulfur is equally important as nitrogen in optimizing crop yields and quality. It contributes to the size and weight of seed crops and enhances the efficiency of nitrogen in protein synthesis. Sulfur is a major factor influencing the partitioning of phosphorus and sulfur and the accumulation of nitrogen in plants, particularly in the context of symbiotic nitrogen fixation in legumes [15]. In oilseed *Brassicas*, the relationship between nitrogen and sulfur is of paramount importance [30]. The application of mineral sulfur fertilizers has been shown to significantly increase seed yield and sulfur uptake in oilseed rape [28].

7. CONCLUSION

Sulfur has gained recognition as the fourth major essential nutrient for plants, alongside Nitrogen (N), Phosphorus (P), and Potassium (K). Achieving high yields of quality crops is only possible when plants have access to the right amount of sulfur. Sulfur is a crucial component of three key amino acids: cysteine, cystein, and methionine, making it essential for protein synthesis in plants. Currently, there exists a gap between the removal and addition of sulfur in agriculture, with a shortfall of 0.5 million tonnes of available sulfur, projected to widen to 2 million tonnes by 2025.

Interestingly, sulfur is the most cost-effective among the four major nutrients required by crops (N, P, K, and S). Its application is not only economical but also yields significant profits compared to other nutrients. To address sulfur deficiency in Indian soils, proper management of sulfur in crop cultivation is imperative. Sulfur application not only sustains high crop yields but also enhances the quality of rapeseed-mustard produce.

Mustard crops exhibit positive responses to sulfur levels ranging from 40-60 kg/ha when applied through sources like Single Super Phosphate (SSP), gypsum, or bentonite sulfur. This sulfur application can lead to an oil content increase of 3-9%. This is particularly significant in the Indian context, as the country faces a shortage of vegetable oils and relies on substantial foreign exchange for imports.

To maximize the benefits of sulfur application in sulfur-deficient soils, measures should be taken to enhance the effectiveness of sulfur-based fertilizers. Strategies should be developed to promote the judicious use of sulfur by combining fertilizer sulfur, byproduct sulfur, and organic manure, ultimately achieving sustainable high productivity in mustard cultivation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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