E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(11): 39-47
Received: 05-09-2025
Accepted: 08-10-2025

Anu Gautam
Lab Technician, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur Madhya Pradesh, India

Rohit Kumar Mishra
Consultant, Food & Agriculture Department, Bureau of Indian Standards, Raipur Branch Office, Chhattisgarh, India

Corresponding Author:
Rohit Kumar Mishra
Consultant, Food & Agriculture Department, Bureau of Indian Standards, Raipur Branch Office, Chhattisgarh, India

Sulphur nutrition in crops: Key to enhanced yield and stress tolerance - a review based on agronomic research

Anu Gautam and Rohit Kumar Mishra

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i11Sa.4167

Abstract
Sulphur (S) plays a crucial role in bolstering crop productivity and resilience against both biotic and abiotic stressors. It facilitates the synthesis of vital compounds like glutathione, glucosinolates, and phytoalexins, pivotal for fortifying plant defences against pathogens and environmental adversities. Scientific endeavors underscore S capacity to augment nutrient uptake, optimize photosynthetic efficacy, and bolster antioxidant mechanisms, thereby enhancing plant endurance to drought, salinity, and heavy metal toxicity. Additionally, S nanoparticles present a promising avenue for enhancing nutrient efficiency and minimizing ecological footprints in agriculture. Future prospects hinge on refining S application methodologies tailored to crop-specific requirements and environmental nuances. Integrating nutrient management practices with biotic stress mitigation strategies holds potential to amplify S efficacy in sustainable farming. Ongoing investigations into S interactions with plant genetics and soil microbiota are poised to deepen insights into its intricate roles and prospective benefits in agroecosystems. S emerges as a versatile ally in elevating crop yield, quality, and resilience amid evolving agricultural landscapes. Addressing future challenges mandates innovative strategies that harness S potential while mitigating environmental impacts, ensuring food security and sustainable agricultural practices in a dynamically changing world.

Keywords: Sulphur, cereal, legume, oilseed, fodder, stress, tolerance

Introduction

Sulphur (S) is a chemical element atomic number 16. In nature it occurs as the pure element or as sulphide and sulphate minerals (Seal 2006) [78]. In the past twenty years, S deficiency has been identified as a significant limitation to crop production globally (Mascagni *et al*., 2008) [56]. S is indispensable for plant growth and development, serving as a fundamental building block of macro-biomolecules and influencing diverse physiological processes (Zenda *et al*., 2021) [102]. S ranks as the thirteenth most abundant element, comprising approximately 0.06-0.10% of the earth crust. Its presence is quite common, with an upper crustal abundance of 621 parts per million. (Rudnick & Gao, 2003 [72]). It has been recognized since 1860 and is vital for plant growth (Always, 1940) [2]. Classified as a macronutrient, S is essential not only for plant vitality but also for improving soil quality, supporting microorganisms, and contributing to the health of both humans and animals. It is increasingly acknowledged as the fourth major plant nutrient, following nitrogen, phosphorus, and potassium. S is crucial for protein synthesis, chlorophyll production, and oil biosynthesis (Sutar *et al*., 2017) [92]. It plays a critical role in the production of vitamins and enzymes necessary for enhancing pulse production. S is also a constituent of essential amino acids such as cystine, cysteine, and methionine. (Zhao *et al*., 1997 [104]; Vidyalakshmi *et al*., 2009 [96]; Kopriva *et al*., 2019) [40]. S concentrations in plants vary widely, typically ranging from 0.05% to 0.90% (Goyal *et al*., 2021) [24]. S requirement for optimal growth varies between 0.1 and 0.5% on dry weight basis of plants and it increases in the order Gramineae < Leguminosae < Cruciferae (Sutar *et al*., 2017) [92].

Historically, S was used in medicine, wool bleaching, and lamp wicks. John White patented a sulphuric acid manufacturing process in 1749 (Kutney, 2023) [47]. S isn't just a nutrient in agriculture but has long been crucial in pest management. From 2500 BC, Sumerians used S against insects, influencing modern fungicides since Homer's time around 1000 BC. Methods in the Middle Ages included burning cuckoo feathers and Bordeaux mixture for vine pests. Lime S was first used in the US in 1883, and Bordeaux mixture in France in 1885. By the late 19th century, sulphuric acid and copper sulphate were herbicides, with Bayer introducing DNOC as a contact pesticide in 1892 (Banaszkiewicz, 2010) [7].

S application boosted yields in over 80% of oilseed rape and cut grass trials, and in 20-60% of cereal trials, with best results on sandy soils, diminishing with higher clay content (Pedersen *et al.*, 1998) [66] These review paper aims to explore the optimal sources of S compounds in agriculture and their broader roles beyond specific crops, encompassing cereals, pulses, and oilseed crops.

Present Status of Sulphur

In 2023, China led global S production with 19 million metric tons, followed by the U.S. with S is primarily processed into sulphuric acid, used in batteries, fertilizers. The global sulphuric acid market was 260 million metric tons in 2021, projected to exceed 300 million metric tons by 2028, with a market value over 12 billion U.S. dollars (Fig. 1). India S production reached 3.5 million metric tons in 2023, a 4.7% increase from the previous year. (Anonymous 2024) [4].

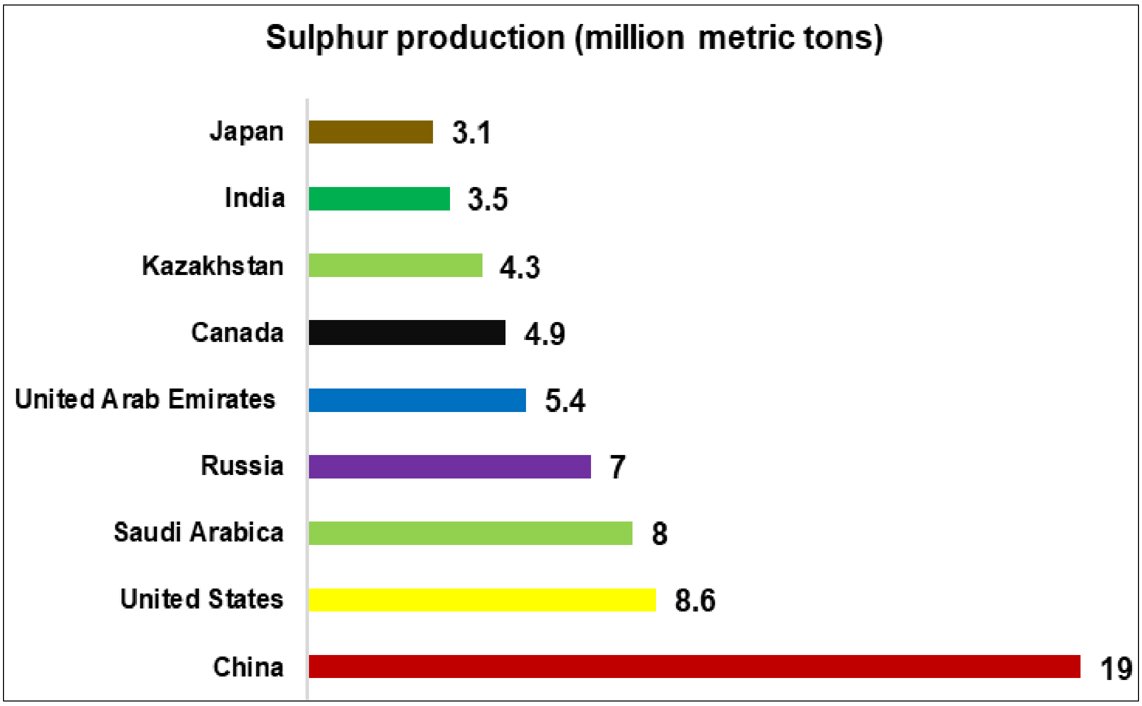

Fig 1: The figure showcases the top S producers, with China at the forefront and Japan rounding out the list. The data underscores the pivotal role of these nations in meeting global S demand.

Trends in Sulphur Deficiency and Soil Health

In the early 1950s, S deficiency was observed only in specific soils, but it has now become a widespread issue. The amount of plant-available S in the soil has decreased by 34-86% between 2000 and 2020, putting crop production at risk (Sharma *et al.*, 2024). A study of 242,827 surface soil samples from 615 districts across 28 states in India found an average S content of 27.0±29.9 mg/kg. S deficiency was present in 58.6% of the soils. Additionally, there were two-nutrient deficiencies: S and zinc (9.3%), S and boron (7.0%), and S and iron (3.3%) (Shukla *et al.*, 2021) [82].

Role of Sulphur in Cultivated Crops

S is one of the essential nutrients that is required for the adequate growth and development of plants. S is a structural component of protein disulfide bonds, amino acids, vitamins, and cofactors. Most of the S in soil is present in organic matter and hence not accessible to the plants (Narayan *et al.*, 2023) [62]. Green plants that are deficient in S exhibit a yellow coloration. S plays a crucial role in photosynthesis, amino acid synthesis, and is an essential component of vitamins such as biotin, lipoic acid, and thiamine, as well as various coenzymes (Imsande., 1998) [31]. In plants, S plays a crucial role in protein synthesis and works synergistically with nitrogen (N). The availability of S and N in plants is closely interconnected, influencing each other's metabolism. S requirement and metabolic processes are tied to N nutrition, just as N metabolism is significantly impacted by the plant's S status (Fig. 2). Similar to how carbon assimilation is linked to nitrate assimilation, S and N pathways are also interconnected, with the abundance of one element affecting the other (Jamal *et al.*, 2010; Anjum *et al.*, 2012) [34, 3].

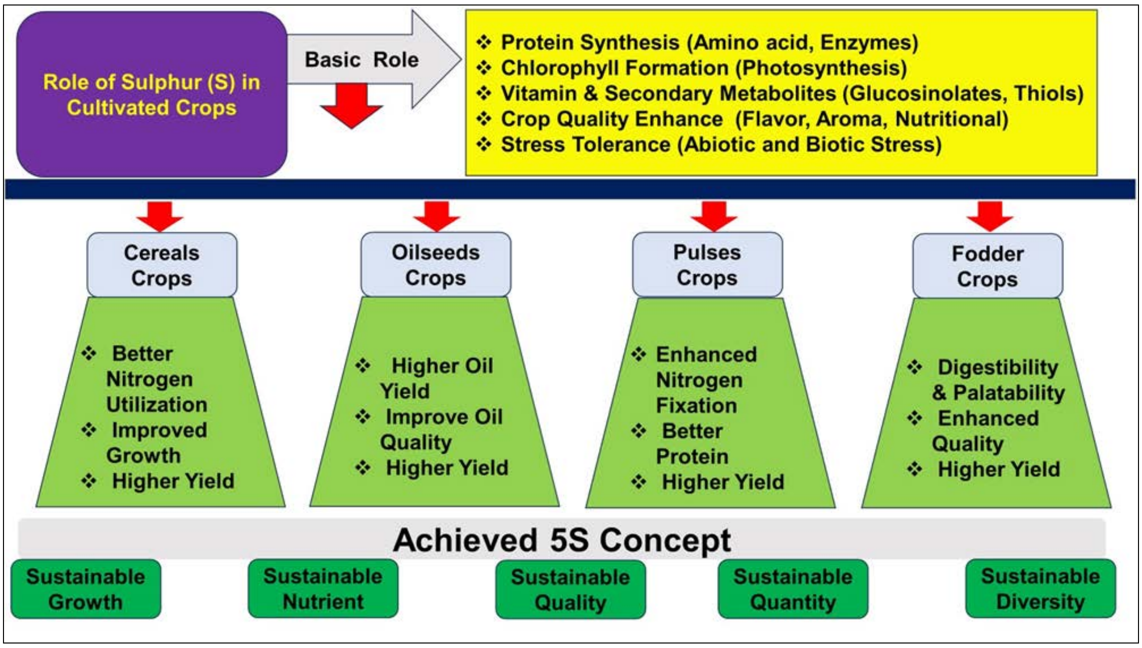

Fig 2: Comprehensive Flowchart Illustrating the Specific Benefits of S Nutrition in Cereals, Oilseed Crops, Pulses, and Fodder Crops

Cereal Crops

S plays a crucial role in ensuring optimal crop growth and maintaining S-containing amino acids in grains. Wheat's reproductive growth is highly sensitive to S deficiency, impacting grain size (Zhao *et al*., 1999) [103]. Kulczycki *et al*. (2022) [43] demonstrated that S application enhances wheat yield under moderate water stress while sustaining nutrient levels in both wheat and maize. Haneklaus *et al*. underscored the importance of timely S application to prevent yield losses in rice. In rice, varying S levels influenced traits such as plant height, panicle length, and grain filling (Islam *et al*., 2016) [32]. Singh *et al*. (2012) [83] highlighted the significant impact of S on rice plant height and yield, showing optimal results at 30 kg S/ha combined with zinc. Singh *et al*. (2019) [90] reported that a combination of 150 kg N and 60 kg S per hectare maximized all growth parameters and yield attributes in rice under field conditions in Moradabad. Sutar *et al*. (2017) [92] observed improved maize growth, yield, and protein content with up to 45 kg S/ha application, noting increased S uptake depending on soil conditions. Sahrawat *et al*. (2008) [73] found that S application enhances S content in sorghum grain and straw, potentially improving nutrient balance and crop quality under rainfed conditions. Hlisnikovský *et al*. (2019) [29] demonstrated that S application in barley boosts grain yield and protein content, essential for mitigating nutrient deficiencies during periods of high temperature and drought. Previous agronomic research on cereal crops such as rice, wheat, maize, barley, and sorghum consistently show that the optimal application rate ranges from 20 to 60 kg/ha. This enhances yield and nutrient uptake, improving grain size and protein content, thereby enhancing crop quality across diverse soil and environmental conditions (Table1).

Table 1: Role of Sulphur in Cereal Crop Yield Enhancement and Recommended Application Rates.

S.NO.	Cereal Crop	Recommended S application rate (kg/ha.)	Yield Increase (%)	Reference
1.	Wheat	20	15-20	McGrath *et al*., 1996 [58]
2.	Maize	30	10-15	Blair *et al*., 2002 [11]
3.	Rice	25	8-12	Singh *et al*., 2001 [86]
4.	Barley	20	12-18	Zhao *et al*., 1999 [103]
5.	Sorghum	25	10-14	Yadav *et al*., 2010 [98]

Legume Crops

S is crucial for legume growth, nodulation, and nitrogen fixation, significantly enhancing yield and nutritional quality (Chaudhary *et al*., 2022) [16]. In chickpea, S application up to 40 kg/ha results in linear increases in growth, yield attributes, seed yield (1665 kg/ha), and stalk yield (2665 kg/ha) (Nawange *et al*., 2011) [63]. Applying 20 kg/ha S in chickpea improves growth, nodulation, and yields of grain and straw (Singh *et al*., 2018) [88]. Optimum S levels, combined with biofertilizers, enhance crop performance in growth and yield. S application at 40 kg/ha in chickpea significantly boosts growth parameters, increases pod and branch numbers, improves seed weight, and enhances grain yield (Makol *et al*., 2020) [51]. In lentils, S is vital for growth, influencing plant height, nodulation, dry weight, pod and seed numbers, test weight, and yields of seed and stover. Applying 30 kg/ha S maximizes yield and economic returns in lentil cultivation (Aparna and Dawson, 2022) [5]. S enhances soybean growth by increasing plant height, seed yield, 1000-seed weight, and straw yield. Application at 20 kg/ha optimizes growth and boosts protein and oil contents, crucial for soybean productivity and quality (Farhad *et al*., 2010) [21]. S is essential for soybean nitrogen metabolism, significantly increasing yield and seed quality. Studies show that applying 40 kg S/ha can increase soybean yields by up to 15% (Głowacka *et al*., 2023) [23]. In lentils, S supports root growth, nodulation, and yield, essential for nutrient uptake and protein synthesis, ensuring robust crop development and improved quality.

During the Kharif season of 2012-2013, applying 40 kg S/ha to green gram significantly improved growth parameters, resulting in an 18.9% higher grain yield (1.07 t/ha) and a 22.1% increase in straw yield compared to the control, along with increased nutrient uptake (Singh, 2017) [85]. During the Rabi season of

2019-2020, applying 30 kg S/ha to green gram significantly enhanced growth attributes and yield parameters, resulting in superior seed yield (979.2 kg/ha) and stover yield (1871.8 kg/ha) compared to lower S levels (Sahu *et al.*, 2021) [74]. In a 2015 study at Adhiparasakthi Agricultural College, applying 30 kg S/ha to green gram, along with the recommended fertilizer dose, significantly improved growth and yield, leading to a 49.32% increase in grain yield (750 kg/ha) and higher net returns (Arunraj *et al.*, 2018) [6]. In a field experiment, applying S at 15 and 30 kg/ha improved soil health and green gram yield. S positively impacted organic carbon, available nitrogen, phosphorus, potassium, pore space, and S content in the soil, enhancing overall crop performance (Kudi *et al.*, 2018) [42]. Previous agronomic research on legume crops such as Chickpea, Lentil, Soybean, Pigeon pea and green gram consistently show that the optimal application rate ranges from 20 to 30 kg/ha.

This enhances yield and nutrient uptake, improving biological nitrogen fixation and protein content, thereby enhancing crop quality across diverse soil and environmental conditions (Table 2).

Table 2: Role of Sulphur in Legume Crop Yield Enhancement and Recommended Application Rates

S.NO.	Legume Crops	Recommended S application rate (kg/ha.)	Yield Increase (%)	Reference
1.	Chickpea	20	15-20	Singh *et al.*, 2012 [89]
2.	Lentil	25	12-18	Ali *et al.*, 2007 [1]
3.	Soybean	30	10-15	Sawan *et al.*, 2008 [77]
4.	Pigeon pea	20	14-19	Deshmukh *et al.*, 2005 [17]
5.	Green gram	25	10-14	Sharma *et al.*, 2004 [59]

Oilseed Crops

In a study conducted during the rabi season of 2019-20 in Ambikapur (C.G.), application of 40 kg S/ha significantly enhanced growth parameters and yield attributes of Indian mustard, with the highest seed yield (1827.16 kg/ha) and oil yield observed at 40 kg S/ha combined with 120 kg N/ha (Mishra *et al.*, 2021) [61]. Piri *et al.* (2011) [68] from Iran reported that applying S at 45 kg/ha markedly increased the leaf area index (LAI) of mustard at 45 and 90 days after sowing (DAS), which was comparable to S application at 30 kg/ha. Ray *et al.* (2014) [71] from West Bengal found that applying 60 kg S/ha significantly increased plant height and dry matter accumulation in Indian mustard at 75 DAS and harvest, as well as the LAI at 40 DAS, which was similar to the effect of 45 kg S/ha. They also noted that applying 45 kg S/ha improved yield attributes such as siliquae per plant, siliqua length, seeds per siliqua, and seed yield per plant.

Begum *et al.* (2012) [9] conducted a field experiment at Gazipur on Indian mustard (BARI Sarisha-15) and found that applying 60 kg S/ha optimally increased growth parameters (plant height, leaf area, dry matter, LAI, crop growth rate, net assimilation rate, and relative growth rate) and protein content, resulting in seed yields of 1990 and 1896 kg/ha, which were significantly higher than the control and comparable to 80 kg S/ha. They reported the highest plant height (103.4 cm and 99.9 cm), crop growth rate (20.34 and 22.24), and net assimilation rate (15.40 and 17.40) at 38-48 DAE with the application of 60 kg S/ha over two years. Kumar and Kumar (2008) [44] observed that different doses of S affected various developmental characteristics of mustard, noting that 50% flowering and 50% podding occurred significantly earlier in plots fertilized with S at 25 kg/ha compared to the control.

Rakesh and Banik (2016) [69] from West Bengal concluded that yield parameters such as siliqua per plant, seeds per siliqua, siliqua length, and 1000 seed weight were maximized with the application of 25 kg S/ha as SSP, which was comparable to 30 kg S/ha as Bentonite-S. Yadav *et al.* (2010) [99] from Allahabad reported that the seed yield at S level of S was 16.83 q/ha compared to 18.33, 19.33, and 18.87 q/ha at S20, S40, and S60 levels of S in Indian mustard, respectively. Singh *et al.* (2012) [87] from Agra concluded that 60 kg/ha S provided significantly higher total biological yield, grain and straw yield, and harvest index compared to 0, 20, and 40 kg/ha S. Banerjee *et al.* (2015) [8] conducted an experiment in West Bengal and reported that applying 60 kg S/ha to Indian mustard significantly increased seed and stover yield by 17.95% and 18.18%, respectively, over zero S. Field experiments in 2010-11 and 2011-12 at Agricultural Research Station, Seethampeta, AP, demonstrated that sulphur application significantly enhanced growth, yield, and oil content in groundnuts. Applying 45 kg/ha of gypsum resulted in the highest plant height, pod yield, and oil content, increasing pod yield by over 50% and oil content by 7.5%-8.8% compared to the control (Rao *et al.*, 2013) [70].

A 2020 Kharif experiment at KVK showed that applying 40 kg/ha of sulphur to the Kadiri 6 groundnut variety significantly increased growth, plant height, nodules, dry weight, pods, kernels, seed yield, haulm yield, and economic returns. Optimal sulphur doses (40 kg/ha) enhance crop development, oil content, and yield by boosting pods per plant (Dileep *et al.*, 2021) [18]. A 2013-14 study revealed that nano-sulphur @ 30 kg/ha significantly outperformed conventional sulphur @ 40 kg/ha in groundnut. Nano-sulphur led to higher sulphur uptake in roots, shoots, kernels, and shells, with the highest pod yield (12.4 g/plant). It also improved oil, crude protein, methionine, cysteine, and amino acid content. The study concluded that nano-sulphur enhances sulphur use efficiency and soil reserves, reducing fertilizer use by 25% without environmental harm (Thirunavukkarasu *et al.*, 2018) [94]. A study at BAU, Mymensingh, found that applying 60 kg/ha of sulphur to the BARI Cheenabadam-8 groundnut variety significantly improved growth and yield parameters, including leaf area, dry matter, branches, pegs, pods, pod yield, and seed yield, suggesting this combination for optimal groundnut yield (Sarkar *et al.*, 2019) [76].

A field study demonstrated that applying 20 kg/ha of sulphur significantly increased sunflower growth parameters and yield. The highest values were observed for plant height (161.80 cm), stem girth (4.80 cm), flower head diameter (15.40 cm), achene number per head (787), 1000 achene weight (50.29 g), grain yield per hectare (650.33 kg), oil content (42.20%), achene yield per plant (39.57 g), and sulphur content in plant straw (0.225%). This indicates the positive role of 20 kg/ha sulphur in enhancing sunflower growth stages and yield attributes (Saleem *et al.*, 2019) [75]. Multiple studies confirm S essentiality for oilseed crops (mustard, groundnut, sunflower, soybean, rapeseed) by promoting oil synthesis and increasing oil content (Table. 3). Its benefits extend beyond oil, enhancing leaf area, dry matter production, branching, peg formation, pod development, and overall seed yield.

Table 3: Role of Sulphur in Oilseed Crop Oil Enhancement and Recommended Application Rates.

S.NO.	Oilseed Crops	Recommended S application rate (kg/ha.)	Oil Increase (%)	Reference
1.	Mustard	40	14-22	Meena *et al*., 2007 [59]
2.	Groundnut	20	10-15	Bhuiyan *et al*., 1998 [10]
3.	Sunflower	30	8-12	Chaterjee *et al*., 2010 [14]
4.	Soybean	20	6-10	Jolley *et al*., 1996 [35]
5.	Rapeseed	40	15-25	Zhao *et al*., 1993 [105]

Fodder Crops

S plays a crucial role in enhancing both the yield and quality of fodder crops through diverse physiological processes. Research indicates that appropriate S application positively influences fodder crop production by enhancing nutrient uptake, protein synthesis, and stress tolerance mechanisms. In fodder sorghum, for example, soil application of 20 kg S/ha increased green and dry fodder yields, along with improving quality parameters such as crude protein content (Chaudhary *et al*., 2018) [15]. Studies consistently demonstrate that S fertilization significantly boosts the yield of fodder crops. Sharma *et al*. (2018) [80] observed a 15% enhancement in biomass and yield of sorghum following S application compared to the control. Similarly, Singh *et al*. (2016) [91] reported a 20% increase in the dry matter yield of berseem (*Trifolium alexandrinum*) with S supplementation. This increase in yield can be attributed to S role in stimulating photosynthesis, thereby enhancing biomass accumulation and crop productivity (Malhi *et al*., 2014) [52].

Furthermore, S enhances the quality attributes of fodder crops, including protein content and digestibility. Kumar *et al*. (2019) [45] demonstrated that S -enriched fodder exhibited higher crude protein levels and improved digestibility, thereby enhancing its nutritional value for livestock. Additionally, S involvement in chlorophyll synthesis enhances the green fodder's colour and palatability, thereby influencing livestock feed intake and nutrient utilization (Kumar *et al*., 2017) [46].

Moreover, S role in activating enzymes and facilitating nutrient uptake, particularly nitrogen and phosphorus, contributes significantly to overall plant health and vigour (Singh and Aggarwal, 2015) [84]. This, in turn, leads to improved crop quality parameters such as fiber content and mineral composition, which are crucial for animal nutrition (Hussain *et al*., 2020) [30]. In conclusion, S application in fodder crop management not only enhances yield by promoting biomass production but also improves nutritional quality, underscoring its critical importance in sustainable livestock feeding systems (Table. 4).

Table 4: Role of Sulphur in Fodder Crops

S.NO.	Benefit	Details	References
1.	Protein Synthesis	S is crucial for the synthesis of cysteine and methionine, essential amino acids in proteins.	McDowell, L.R. (2003) [57]
2.	Vitamin Synthesis	Contributes to the synthesis of biotin and thiamine, important vitamins for livestock health.	NRC (National Research Council), 2001 [65]
3.	Detoxification	Aids in detoxifying harmful substances in the liver, promoting overall health.	Miller, W.J., & Davis, C.L. (1992) [60]
4.	Joint Health	Supports the synthesis of collagen and cartilage, crucial for joint health in livestock.	McDowell, L.R. (2003) [57]

Protection against Abiotic Stress

S dioxide (SO2) pretreatment has been shown to significantly enhance drought tolerance in wheat by increasing survival rates, maintaining relative water content, and bolstering antioxidant enzyme activities. This treatment effectively reduces oxidative damage and regulates proline accumulation and H2S signaling under drought stress conditions (Li *et al*., 2021) [48]. Moreover, S fertilizers, particularly K2SO4 (17 % S), have been demonstrated to improve maize's drought resilience by enhancing biomass production, optimizing nutrient uptake, promoting efficient gas exchange, and boosting antioxidant enzyme activity.

These enhancements ultimately lead to increased yield even under water-deficient conditions (Usmani *et al*., 2020) [95]. Additionally, studies have highlighted SO2's role in enhancing foxtail millet's ability to withstand drought stress by reducing stomatal aperture, increasing proline accumulation, and fortifying antioxidant defences against oxidative damage (Han *et al*., 2019) [25]. Furthermore, in Arabidopsis, SO2 supplementation has been found to bolster drought tolerance mechanisms through improvements in photosynthesis, antioxidant defence systems, S assimilation, and osmotic adjustments (Li *et al*., 2022) [49]. S's contribution to enhancing plant salinity tolerance is notable as well, maintaining nutrient balance and supporting essential S-containing compounds crucial for stress adaptation in crops such as rice and wheat (Nazar *et al*., 2011 [64]; Jahan *et al*., 2021) [33]. Moreover, S facilitates plant tolerance to heavy metals by enhancing hydrogen sulphide (H2S) signaling, thereby mitigating stress effects (Luo *et al*., 2020) [50].

Additionally, S nanoparticles (SNPs) have been found to alleviate mercury toxicity in Brassica napus by reducing mercury accumulation, oxidative stress, and enhancing nutrient uptake, biomass, and antioxidant defences (Yuan *et al*., 2021) [100]. Overall, S's multifaceted roles in enhancing plant resilience to various stresses underscore its importance in sustainable agricultural practices (Table. 5).

Table 5: Role of Sulphur in Enhancing Tolerance to Different Abiotic Stresses

S.NO.	Abiotic Stress Factor	Role of S	References
1.	Osmotic Stress	Maintains cell turgor pressure by osmotic regulation.	Hawkesford, M.J. (2012) [28]
2.	Oxidative Stress	Acts as a component of antioxidant enzymes to scavenge reactive oxygen species.	Kopriva, S., & Rennenberg, H. (2004) [39]
3.	Salinity Stress	Enhances synthesis of compatible solutes and antioxidants, reducing ion toxicity.	Khan, M.I.R. *et al.* (2016) [37]
4.	Heat Stress	Supports heat shock proteins and protects protein integrity under high temperatures.	Malik, A.I. *et al.* (2017) [53]

Protection against Biotic Stress

S plays a critical role in enhancing plant disease resistance through the synthesis of essential compounds such as glutathione, glucosinolates, and phytoalexins. These compounds are pivotal in plants' defence mechanisms against various pathogens. Studies have shown that S fertilization increases the production of these defence compounds, thereby reducing susceptibility to diseases in crops like oilseed rape and tomato (Marazzi, 2003 [54]; Marazzi *et al.*, 2004 [55]; Bloem *et al.*, 2005 [13]; Dubuis *et al.*, 2005 [19]; Haneklaus *et al.*, 2006 [27]; Kruse *et al.*, 2007 [41]; Zappalà *et al.*, 2012 [101]; Pérez-Guerrero and Molina, 2016) [67]. This enhancement in disease resistance highlights S's role in improving plant health and resilience under different environmental conditions, contributing significantly to sustainable agricultural practices (Table. 6).

Table 6: Role of Sulphur in Enhancing Tolerance to Different Biotic Stresses

S.NO.	Biotic Stress Factor	Role of S	Reference
1.	Powdery Mildew Disease	Acts as a fungicide by altering the pH on plant surfaces, preventing fungal spore germination.	Elmer, W.H. (2013) [20]
2.	Pathogen Attack	Enhances synthesis of glucosinolates and phytoalexins, boosting plant resistance.	Francisco, M.A. *et al.* (2016) [22]
3.	Insect Herbivory	Strengthens cell walls and induces chemical defences against herbivores.	Wittstock, U., & Burow, M. (2010) [97]
4.	Indirect Défense	Supports production of volatile organic compounds that attract natural enemies of pests.	Khaling, E. *et al.* (2015) [36]
5.	Antimicrobial Activity	Exhibits direct antimicrobial effects against pathogens.	Bloem, E., & Haneklaus, S. (2016) [12]

Conclusion

Based on the comprehensive review of S role in crop production and stress tolerance, S emerges as a pivotal element in enhancing both yield and quality across various crop types. S application significantly improves crop growth and development by promoting the synthesis of crucial compounds like cysteine, glutathione, glucosinolates, and phytoalexins. These compounds not only bolster plant defence mechanisms against pathogens but also contribute to stress tolerance against abiotic factors such as drought, salinity, and heavy metal toxicity. In addition to its direct effects on biochemical pathways and nutrient uptake, S's role in enhancing antioxidant defences and osmotic regulation underscores its importance in mitigating oxidative stress and maintaining cell turgor under adverse environmental conditions. Moreover, S nanoparticles show promise in reducing heavy metal toxicity and enhancing nutrient use efficiency, paving the way for sustainable agricultural practices.

Future research should focus on optimizing S application strategies tailored to specific crop requirements and environmental conditions. Integrating S management with other nutrient regimes and biotic stress management strategies can further enhance crop resilience and productivity. Continued exploration of S's interactions with plant genetics and its effects on soil microbiota will provide deeper insights into its multifaceted roles in sustainable agriculture.

In conclusion, S diverse impacts on crop physiology, stress tolerance, and disease resistance highlight its critical role in ensuring food security and sustainable agricultural practices in the face of changing climatic conditions and environmental challenges.

Reference

1. Ali M, Kumar S. Effect of sulphur fertilization on yield and quality of lentil. *Indian J Agron* 2007;52(1):60-63.
2. Alway FJ. A nutrient element slighted in agricultural research. *Agron J* 1940;32(12):913-21.
3. Anjum NA, Gill SS, Umar S, Ahmad I, Duarte AC, Pereira E, *et al*. Improving growth and productivity of oleiferous *Brassicas* under changing environment: significance of nitrogen and sulphur nutrition, and underlying mechanisms. *ScientificWorldJournal* 2012;2012(1):657808.
4. Anonymous. Statista. https://www.statista.com/statistics/1031181/sulphur-production-globally-by-country/. Accessed 2024 Jul 3.
5. Aparna B, Dawson J. Effect of bio-fertilizers and sulphur on growth and yield of lentil (*Lens culinaris* M.). Int J Plant Soil Sci 2022;34(19):200-4.
6. Arunraj M, Vasanthi D, Mansingh MDI. Effect of sulphur on growth and yield of greengram [*Vigna radiata*]. Int J Sci Environ Technol 2018;7(5):1861-7.
7. Banaszkiewicz T. Evolution of pesticide use. Contemp Probl Manage Environ Prot 2010;5:7-18.
8. Banerjee H, Ray K, Sevgupta K, Pal AK. Effect of sulphur fertilization on yield, sulphur uptake and quality of Indian mustard (*Brassica juncea* L.) under varied irrigation regimes. Plant Soil Environ 2015;61(1):6-10.
9. Begum F, Hossain F, Mondal RI. Influence of sulphur on morpho-physiological and yield parameters of rapeseed (*Brassica campestris* L.). *Bangladesh J Agril Res* 2012;37(4):645-65.
10. Bhuiyan MAH, Mian MAK, Tareque MI. Effect of sulphur and boron on the yield and oil content of groundnut. Bangladesh J Agric Res 1998;23(2):353-9.
11. Blair GJ, Chinoim N, Lefroy RDB, Anderson GC, Crocker GJ. Soil nutrient availability and yield response to sulphur in maize. Field Crops Res 2002;77(2-3):113-24.
12. Bloem E, Haneklaus S. Sulfur as an antimicrobial and as part of defense mechanisms in higher plants. In: Hell R, Dahl C, editors. Sulfur Metabolism in Phototrophic Organisms. Dordrecht: Springer; 2016. p. 231-50.
13. Bloem E, Haneklaus S, Schnug E. Significance of sulfur compounds in the protection of plants against pests and diseases. J Plant Nutr 2005;28(5):763-84.
14. Chatterjee R, Ghosh S. Effect of sulphur fertilization on yield, oil content, and quality of sunflower. J Plant Nutr 2010;33(11):1602-12.
15. Chaudhary PP, Patel KH, Italia AP, Garaniya NH, Patel DD. Effect of sulphur and zinc with organics on yield and quality of

fodder sorghum under south Gujarat condition. J Pharmacogn Phytochem 2018;7(5):1711-4.
16. Chaudhary S, Dhanker R, Kumar R, Goyal S. Importance of legumes and role of sulphur oxidizing bacteria for their production: a review. Legume Res Int J 2022;45(3):275-84.
17. Deshmukh VK, Aher VB. Impact of sulphur fertilization on yield and quality of pigeonpea. Legume Res 2005;28(3):218-20.
18. Dileep D, Singh V, Tiwari D, George GS, Swathi P. Effect of variety and sulphur on growth and yield of groundnut (*Arachis hypogaea* L.). Biol Forum Int J 2021;13:475-8.
19. Dubuis PH, Marazzi C, Städler E, Mauch F. Sulphur deficiency causes a reduction in antimicrobial potential and leads to increased disease susceptibility of oilseed rape. J Phytopathol 2005;153(1):27-36.
20. Elmer WH. Sulfur and plant disease control. J Plant Nutr Soil Sci 2013;176(2):231-41.
21. Farhad ISM, Islam MN, Hoque S, Bhuiyan MSI. Role of potassium and sulphur on the growth, yield and oil content of soybean (*Glycine max* L.). Acad J Plant Sci 2010;3(2):99-103.
22. Francisco MA, *et al*. Glucosinolate metabolism, functionality and breeding for enhanced plant defense. In: Jansen MAK, *et al*, editors. *Adv Bot Res* 2016;80:201-45.
23. Głowacka A, Jariene E, Flis-Olszewska E, Kiełtyka-Dadasiewicz A. The effect of nitrogen and sulphur application on soybean productivity traits in temperate climate conditions. *Agronomy* 2023;13(3):780-9.
24. Goyal D, Franzen DW, Chatterjee A. Do crops' responses to sulphur vary with its forms. Agrosyst Geosci Environ 2021;4(3):e20201.
25. Han Y, Yang H, Wu M, Yi H. Enhanced drought tolerance of foxtail millet seedlings by sulfur dioxide fumigation. Ecotoxicol Environ Saf 2019;178:9-16.
26. Haneklaus S, Schnug E. Diagnosis of crop sulphur status and application of X-ray fluorescence spectroscopy for the sulphur determination in plant and soil materials. Commun Soil Sci Plant Anal 1994;25:2183-94.
27. Haneklaus S, Bloem E, Schnug E. Disease control by sulphur induced resistance. Aspects Appl Biol 2006;79:221-4.
28. Hawkesford MJ. Sulfur metabolism in plants: regulation of sulfate transporters and assimilatory enzymes. In: Hell R, Dahl C, editors. Sulfur Metabolism in Phototrophic Organisms. Dordrecht: Springer; 2012. p. 65-90.
29. Hlisnikovský L, Čermák P, Kunzová E, Barłóg P. The effect of application of potassium, magnesium and sulphur on wheat and barley grain yield and protein content. Plant Soil Environ 2019;65(12):583-90.
30. Hussain S, *et al*. Impact of sulphur on fiber content and mineral composition of fodder crops. J Agric Sci Technol 2020;22(5):1123-32.
31. Imsande J. Iron, sulfur, and chlorophyll deficiencies: a need for an integrative approach in plant physiology. Physiol Plant 1998;103(1):139-44.
32. Islam AS, Rana MS, Rahman MM, Mian MJA, Rahman MM, Rahman MA, *et al*. Growth, yield and nutrient uptake capacity of rice under different sulphur levels. Turk J Agric Food Sci Technol 2016;4(7):557-65.
33. Jahan B, Rasheed F, Sehar Z, Fatma M, Iqbal N, Masood A, *et al*. Coordinated role of nitric oxide, ethylene, nitrogen, and sulfur in plant salt stress tolerance. *Stresses* 2021;1(3):181-99.
34. Jamal A, Moon YS, Zainul Abdin M. Sulphur a general overview and interaction with nitrogen. Aust J Crop Sci 2010;4(7):523-9.
35. Jolley VD, Brown JC, Welch RM. Nutrient uptake and utilization by soybean. J Plant Nutr 1996;19(6):909-21.
36. Khaling E, *et al*. Volatile-mediated interactions between *Brassica* seedlings and soilborne fungi under natural conditions. Plant Soil 2015;392(1-2):195-208.
37. Khan MIR, *et al*. Sulfur assimilation and abiotic stress in plants. In: Hossain MA, *et al*, editors. Sulfur Metabolism in Higher Plants. Boca Raton: CRC Press; 2016. p. 145-67.
38. Khan NA, Khan MIR, Asgher M, Fatma M, Masood A, Syeed S. Salinity tolerance in plants: revisiting the role of sulfur metabolites. J Plant Biochem Physiol 2014;2(2):10-4172.
39. Kopriva S, Rennenberg H. Control of sulfur assimilation and glutathione synthesis: interaction with N and C metabolism. In: De Kok LJ, editor. Integration of Primary Metabolism and Secondary Metabolite Production. Dordrecht: Springer; 2004. p. 211-32.
40. Kopriva S, Malagoli M, Takahashi H. Sulphur nutrition: impacts on plant development, metabolism, and stress responses. *J Exp Bot* 2019;70(16):4069-73.
41. Kruse C, Jost R, Lipschis M, Kopp B, Hartmann M, Hell R. Sulfur-enhanced defence: effects of sulfur metabolism, nitrogen supply, and pathogen lifestyle. *Plant Biol* 2007;9(5):608-19.
42. Kudi S, Swaroop N, David AA, Thomas T, Hasan A, Rao S. Effect of different levels of sulphur and zinc on soil health and yield of greengram (*Vigna radiata* L.) var. Patidar-111. J Pharmacogn Phytochem 2018;7(3):2271-4.
43. Kulczycki G, Sacała E, Chohura P, Załuska J. Maize and wheat response to drought stress under varied sulphur fertilisation. Agronomy 2022;12(5):1076-83.
44. Kumar A, Kumar S. Crop growth rate and developmental characteristics of Indian mustard var. Vardan to varying levels of nitrogen and sulphur. Indian J Agric Res 2008;42:112-5.
45. Kumar A, *et al*. Sulphur fertilization and its effect on protein content and digestibility of fodder crops. J Appl Anim Res 2019;47(1):448-54.
46. Kumar P, *et al*. Influence of sulphur and boron on the quality of fodder crops. Legume Res Int J 2017;40(3):494-7.
47. Kutney G. Sulphur: History, *Technology*, Applications and Industry. Amsterdam: Elsevier; 2023.
48. Li LH, Yi HL, Liu XP, Qi HX. Sulfur dioxide enhances drought tolerance of wheat seedlings through H_2S signaling. *Ecotoxicol Environ Saf* 2021;207:111248.
49. Li L, Yi H. Enhancement of drought tolerance in *Arabidopsis* plants induced by sulfur dioxide. Ecotoxicology 2022;31(4):637-48.
50. Luo S, Calderón-Urrea A, Yu J, Liao W, Xie J, Lv J, *et al*. The role of hydrogen sulfide in plant alleviation of heavy metal stress. Plant Soil 2020;449:1-10.
51. Makol FH, Gandahi AW, Memon AH, Jatoi SH, Abbasi JA, Buriro IA. Effect of sulphur application on growth and yield of chickpea (*Cicer arietinum* L.) under rice-chickpea cropping system. J Appl Res Plant Sci 2020;1(1):9-12.
52. Malhi SS, *et al*. Sulphur and nitrogen effects on growth, yield, and nutrient uptake of canola under semi-arid conditions. Can J Plant Sci 2014;94(7):1205-14.
53. Malik AI, *et al*. Impact of sulfur on heat stress tolerance in crop plants. In: Hasanuzzaman M, *et al*, editors. Plant Acclimation to Environmental Stress. Cham: Springer; 2017. p. 301-18.
54. Marazzi C. Plant Sulphur Nutrition Influencing Host-Plant Selection and Performance of Insect Herbivores [dissertation]. Basel: University of Basel; 2003.
55. Marazzi C, Patrian B, Städler E. Secondary metabolites of the leaf surface affected by sulphur fertilisation and perceived by the cabbage root fly. *Chemoecology* 2004;14:87-94.
56. Mascagni HJ Jr, Harrison SA, Padgett GB. Influence of sulphur fertility on wheat yield performance on alluvial and upland soils. *Commun Soil Sci Plant Anal* 2008;39:2133-45.
57. McDowell LR. Minerals in Animal and Human Nutrition. 2nd ed. Amsterdam: Elsevier Science; 2003.
58. McGrath SP, Zhao FJ, Blake-Kalff MMA. Sulphur deficiency in crops and its alleviation: a global overview. Adv Agron 1996;57:81-144.
59. Meena RL, Sharma RP. Response of Indian mustard (*Brassica juncea*) to different sources and levels of sulphur under irrigated conditions. Indian J Agron 2007;52(4):317-20.
60. Miller WJ, Davis CL. Mineral Nutrition of Livestock. 4th ed. New York: CAB Int; 1992.
61. Mishra RK, Patel A, Gupta A, Vishal K, Gupta SK. Interaction effect of varying level of nitrogen and sulphur fertilizers on growth and yield of Indian mustard (*Brassica juncea* L.) under Northern hill zone of Chhattisgarh. IJCS 2021;9(1):2574-2577.
62. Narayan OP, Kumar P, Yadav B, Dua M, Johri AK. Sulphur

nutrition and its role in plant growth and development. Plant Signaling & Behavior 2023;18(1):2030082.
63. Nawange DD, Yadav AS, Singh RV. Effect of phosphorus and sulphur application on growth, yield attributes and yield of chickpea (*Cicer arietinum* L.). Legume Research - An International Journal 2011;34(1):48-50.
64. Nazar R, Iqbal N, Masood A, Syeed S, Khan NA. Understanding the significance of sulfur in improving salinity tolerance in plants. Environmental and Experimental Botany 2011;70(2-3):80-87.
65. National Research Council (NRC). Nutrient Requirements of Dairy Cattle. 7th ed. Washington (DC): National Academies Press; 2001.
66. Pedersen CA, Knudsen L, Schnug E. Sulphur fertilisation. Sulphur in Agroecosystems 1998;115-134.
67. Pérez-Guerrero S, Molina JM. Laboratory approach to the use of sulphur and kaolin as preventive control against *Drosophila suzukii*. Spanish Journal of Agricultural Research 2016;14(2):e10SC01-e10SC01.
68. Piri I, Nik MM, Tavassoli A, Rastegaripour F, Babaeian M. Effect of irrigation frequency and application levels of sulphur fertilizer on water use efficiency and yield of Indian mustard (*Brassica juncea*). African Journal of Biotechnology 2011;10(55):11459-11467.
69. Rakesh, Banik. Evaluation of combined effect of sulphur and nitrogen dose on *Brassica juncea* under the Bundelkhand region of Madhya Pradesh, India. Plant Archives 2016;16(1):306-308.
70. Rao KT, Rao AU, Sekhar D. Effect of sources and levels of sulphur on groundnut. Journal of Academia and Industrial Research 2013;2(5):268-270.
71. Ray K, Pal AK, Banerjee H, Phonglosa A. Correlation and path analysis studies for growth and yield contributing traits in Indian mustard (*Brassica juncea* L.). Int J Bio Resour Stress Manag 2014;5(2):200-206.
72. Rudnick RL, Gao S. Composition of the Continental Crust. In: Rudnick RL, editor. Treatise on Geochemistry. Vol 3. Amsterdam: Elsevier; 2003. p.1-64.
73. Sahrawat KL, Rego TJ, Wani SP, Pardhasaradhi G. Sulfur, boron, and zinc fertilization effects on grain and straw quality of maize and sorghum grown in semi-arid tropical region of India. Journal of Plant Nutrition 2008;31(9):1578-1584.
74. Sahu S, Shankar T, Maitra S, Adhikary R, Mondal T, Duvvada SK. Impact of phosphorus and sulphur on the growth and productivity of green gram (*Vigna radiata*). Research on Crops 2021;22(4):785-791.
75. Saleem M, Elahi E, Gandahi AW, Bhatti SM, Ibrahim H, Ali M. Effect of sulphur application on growth, oil content and yield of sunflower. Sarhad Journal of Agriculture 2019;35(4).
76. Sarkar MAR, Uddin MR, Sarker UK, Kaysar MS, Saha PK. Effect of variety and sulphur on yield and yield components of groundnut: variety and sulphur effect on groundnut. Journal of the Bangladesh Agricultural University 2019;17(1):1-8.
77. Sawan ZM, Hafez SA, Basyony AE. Effect of sulphur application on soybean yield and quality. Field Crops Research 2008;106(2):109-114.
78. Seal RR. Sulphur isotope geochemistry of sulfide minerals. Reviews in Mineralogy and Geochemistry 2006;61(1):633-677.
79. Sharma RK, Cox MS, Oglesby C, Dhillon JS. Revisiting the role of sulphur in crop production: a narrative review. Journal of Agriculture and Food Research 2024;15:101013.
80. Sharma RK, *et al*. Effect of sulphur and nitrogen application on growth, yield and nutrient uptake of sorghum (*Sorghum bicolor* (L.) Moench) under rainfed conditions. Journal of Agrometeorology 2018;20(2):162-166.
81. Sharma VK, Singh RP. Response of mungbean to sulphur and phosphorus fertilization. Journal of Agricultural Science 2004;142(3):309-315.
82. Shukla AK, Behera SK, Prakash C, Tripathi A, Patra AK, Dwivedi BS, *et al*. Deficiency of phyto-available sulphur, zinc, boron, iron, copper and manganese in soils of India. Scientific Reports 2021;11(1):19760.
83. Singh AK, Meena MK, Upadhyaya A. Effect of sulphur and zinc on rice performance and nutrient dynamics in plants and soil of Indo-Gangetic plains. Journal of Agricultural Science 2012;4(11):162-170.
84. Singh B, Aggarwal P. Sulphur nutrition: a critical nutrient for enhancing crop productivity and quality. Communications in Soil Science and Plant Analysis 2015;46(8):943-953.
85. Singh DP. Effect of potassium and sulphur on performance of green gram (*Vigna radiata*) in alluvial soil. Annals of Plant and Soil Research 2017;19(2):223-226.
86. Singh MV. Sulphur management for enhancing productivity and quality of rice in Indian soils. Indian Journal of Agronomy 2001;46(4):687-693.
87. Singh MV, Tiwari KN. Sulphur management for increasing yield and quality of chickpea. Journal of Food Legumes 2012;25(4):310-313.
88. Singh R, Pratap T, Singh D, Singh G, Singh AK. Effect of phosphorus, sulphur and biofertilizers on growth attributes and yield of chickpea (*Cicer arietinum* L.). Journal of Pharmacognosy and Phytochemistry 2018;7(2):3871-3875.
89. Singh R, Singh SB, Manhas SS, Kumar A. Effect of different levels of sulphur and varieties on growth, yield and quality of Indian mustard. Int J Plant Sci 2012;7(2):290-294.
90. Singh S, Singh V, Khanna R, Kumar P, Shukla R. Effect of nitrogen and sulphur fertilization on growth and yield of rice (*Oryza sativa* L.). Progressive Research 2019;14(1):526-530.
91. Singh V, *et al*. Impact of sulphur and zinc on growth, yield attributes and quality of berseem (*Trifolium alexandrinum* L.). Indian Journal of Agricultural Sciences 2016;86(12):1567-1572.
92. Sutar RK, Pujar AM, Kumar BA, Hebsur NS. Sulphur nutrition in maize - a critical review. Int J Pure Appl Biosci 2017;5(6):1582-1596.
93. Sutar RK, Pujar AM, Kumar BA, Hebsur NS. Sulphur nutrition in maize - a critical review. Int J Pure Appl Biosci 2017;5(6):1582-1596.
94. Thirunavukkarasu M, Subramanian KS, Kannan P, Balaji T. Response of nano-sulphur to the groundnut. IJCS 2018;6(3):2067-2072.
95. Usmani MM, Nawaz F, Majeed S, Shehzad MA, Ahmad KS, Akhtar G, *et al*. Sulfate-mediated drought tolerance in maize involves regulation at physiological and biochemical levels. Scientific Reports 2020;10(1):1147.
96. Vidyalakshmi R, Paranthaman R, Bhakyaraj R. Sulphur oxidizing bacteria and pulse nutrition - a review. World Journal of Agricultural Sciences 2009;5(3):270-278.
97. Wittstock U, Burow M. Glucosinolate breakdown in *Arabidopsis*: mechanisms, regulation and biological significance. In: Sørensen H, *et al*., editors. The Biology of *Brassica* Coenospecies. Amsterdam: Elsevier; 2010.
98. Yadav AL, Kumar A, Chauhan RPS. Effect of sulphur fertilization on yield and quality of sorghum. Journal of Agricultural Science 2010;2(2):221-227.
99. Yadav RP, Tripathi ML, Trivedi SK. Yield and quality of Indian mustard (*Brassica juncea*) as influenced by irrigation and nutrient levels. Indian Journal of Agronomy 2010;55(1):56-59.
100. Yuan H, Liu Q, Guo Z, Fu J, Sun Y, Gu C, *et al*. Sulfur nanoparticles improved plant growth and reduced mercury toxicity via mitigating the oxidative stress in *Brassica napus* L. Journal of Cleaner Production 2021;318:128589.
101. Zappala L, Siscaro G, Biondi A, Mollá O, González-Cabrera J, Urbaneja A. Efficacy of sulphur on *Tuta absoluta* and its side effects on the predator *Nesidiocoris tenuis*. Journal of Applied Entomology 2012;136(6):401-409.
102. Zenda T, Liu S, Dong A, Duan H. Revisiting sulphur—the once neglected nutrient: its roles in plant growth, metabolism, stress tolerance and crop production. Agriculture 2021;11(7):626.
103. Zhao FJ, Salmon SE, Withers PJA, Monaghan JM, Evans EJ, Shewry PR, McGrath SP. Variation in the breadmaking quality and rheological properties of wheat in relation to sulphur nutrition under field conditions. Journal of Cereal Science 1999;30(1):19-31.
104. Zhao FJ, Withers PJA, Evans EJ, Monaghan J, Salmon SE,

Shewry PR, *et al*. Sulphur nutrition: an important factor for the quality of wheat and rapeseed. Soil Science and Plant Nutrition 1997;43(Suppl 1):1137-1142.
105. Zhao FJ, McGrath SP. Sulphur deficiency and its effects on yield and quality of rapeseed. Journal of Agricultural Science 1993;121(3):287-294.
106. Zhao FJ, Wood AP, McGrath SP. Sulphur deficiency and its effects on yield and quality of wheat. Plant and Soil 1999;216(1-2):83-90.