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# Role of sulphur in plants and soil: Advances and implications

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## ABSTRACT

Sulphur, a vital nutrient for plants, plays a crucial role in the formation of proteins, vitamins, and chlorophyll. This paper investigates the significance of sulphur in both plants and soil, emphasizing its essential functions in plant growth and development. The authors have explored how sulphur contributes to the synthesis of important amino acids, supports enzyme activity, and is necessary for chlorophyll production, which is key for photosynthesis. The recent advancements in the availability of sulphur in soil, its cyclical transformation through ecosystems, and innovative fertilization methods that ensure plants get the sulphur they need has been highlighted. The paper reviews the negative impacts of both sulphur deficiency and excess, such as poor plant health and soil degradation, and presents new technologies and strategies for monitoring and managing sulphur levels effectively. This research is particularly valuable because it sheds light on modern techniques and approaches that can significantly enhance crop health and soil quality. Application of these advanced technologies and methods will be helpful for supporting sustainable agricultural practices and better environmental management which in turn may lead to more resilient farming systems and improved food security.

**Key words:** Amino acids, chlorophyll, plant growth, soil quality, sulphur, sustainable agriculture

## INTRODUCTION

Sulphur (S) might not be as widely discussed as other macronutrients like nitrogen (N), phosphorus (P), or potassium (K), but it is just as essential for plant health and productivity. Often referred to as the "fourth major nutrient," sulphur plays several critical roles in plant physiology and biochemistry (Nawaz et al., 2020). It is a key component of certain amino acids, such as cysteine and methionine, which are building blocks for proteins. These amino acids are integral to the structure and function of enzymes, which drive numerous biochemical reactions within the plant (Guo et al., 2021). Furthermore, sulphur is vital for the synthesis of vitamins and cofactors, which support various metabolic processes. One of its most notable roles is in the formation of chlorophyll, the green pigment responsible for photosynthesis (Narayan et al., 2023). Photosynthesis is the process by which plants convert light energy into chemical energy, producing the carbohydrates that fuel their growth and development. Without adequate sulphur, plants cannot produce sufficient chlorophyll, leading to reduced photosynthetic capacity and, consequently, poor growth and lower yields (Zenda et al., 2021). Despite its importance, sulphur has often been overlooked in both research and practical agriculture compared to other nutrients. This oversight can lead to deficiencies, which may go unrecognized until significant damage has occurred. Sulphur deficiency can manifest as chlorosis (yellowing of the leaves), stunted growth, and poor overall plant health (Zenda et al., 2021; Morya et al., 2023). In addition to affecting plant vitality, sulphur deficiencies can also have broader environmental and economic impacts, reducing crop yields and quality (Chaudhary et al., 2023). Recent advancements in agricultural science and technology have brought renewed attention to the importance of sulphur. Improved understanding of sulphur cycling in the soil, developments in sulphur-enriched fertilizers, and the use of precision agriculture technologies are helping to ensure that crops receive the appropriate levels of this essential nutrient (Dotaniya et al., 2024; Dar et al., 2025). Research into the bioavailability of sulphur in soil, influenced by factors such as soil pH, texture, organic matter content, and microbial activity, is providing deeper insights into how to manage sulphur effectively (Shah et al., 2022; Yasin, 2024). These insights are critical for developing strategies to address both sulphur deficiency and surplus, ensuring optimal plant health and soil quality.

This paper can explore the multifaceted role of sulphur in plants and soil, highlighting recent advances in our understanding and management of this crucial nutrient. By examining the latest research and emerging technologies, we aim to provide a comprehensive overview of how sulphur can be managed to promote sustainable agriculture and environmental stewardship.

## ROLE OF SULPHUR IN PLANTS

Sulphur is indispensable for plant growth and development, functioning in various biochemical and physiological processes. Its roles extend beyond mere presence in proteins and enzymes to influencing overall plant health and productivity (Fig. 1). Here, we delve deeper into the critical functions sulphur performs in plants.

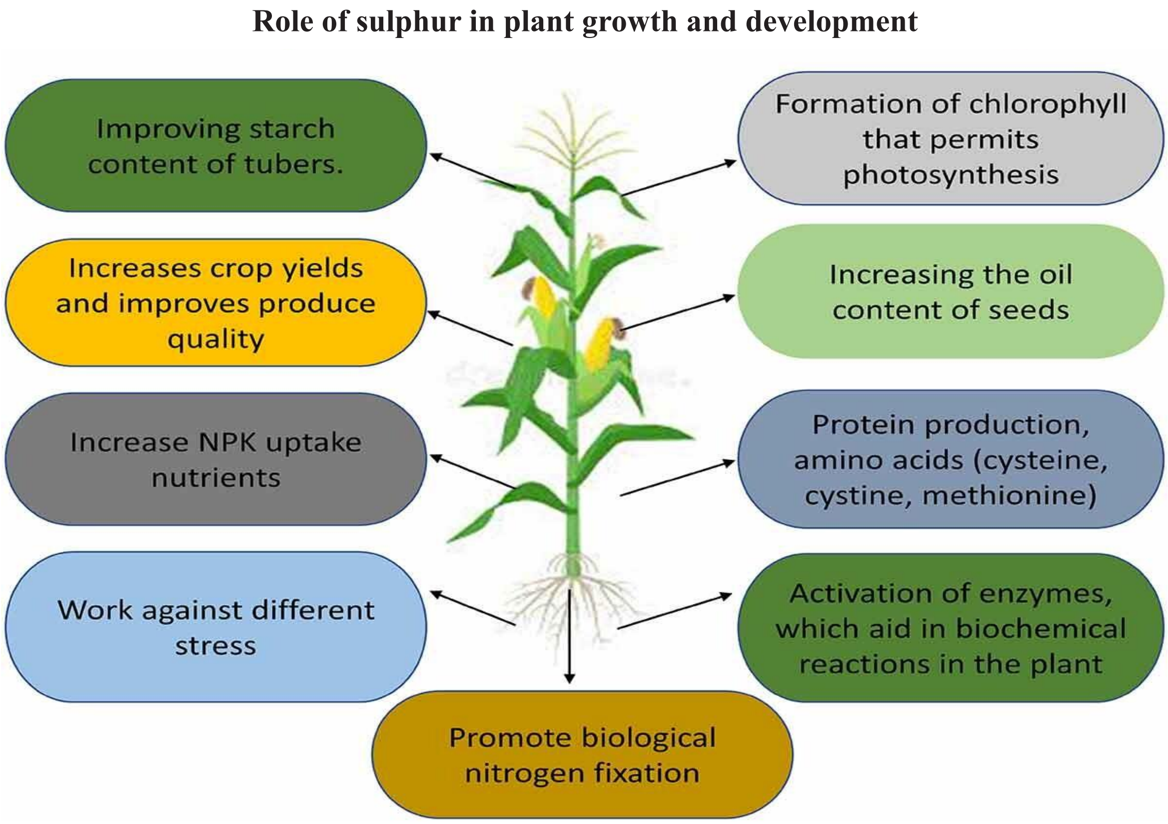


**Fig. 1.** Schematic representation of the role of sulphur in plant growth and development (Source: Narayan et al., 2023)

**Amino acid and protein synthesis**

Sulphur is a fundamental element in the synthesis of amino acids, particularly cysteine and methionine. These sulphur-containing amino acids are integral components of proteins and play a vital role in plant structure and function (Ahmad et al., 2017; Ihsan et al., 2019). Cysteine is not only a building block for proteins but also a precursor for other important biomolecules like glutathione, which is crucial for plant stress responses and detoxification processes (Hendrix et al., 2017; Alvi et al., 2023). Methionine, on the other hand, is essential for initiating protein synthesis and is a precursor for ethylene, a plant hormone involved in growth and stress responses (Shi et al., 2025).

**Enzyme function and metabolism**

Sulphur is a component of several key enzymes and coenzymes that facilitate metabolic processes within plants. Enzymes containing sulphur play a critical role in the assimilation of nitrogen, which is essential for protein synthesis and plant growth (Zenda et al., 2021; Narayan et al., 2023). For instance, the enzyme ferredoxin, which contains sulphur, is involved in photosynthesis and nitrogen fixation. Sulphur is also a component of coenzyme A, which is pivotal in fatty acid metabolism and the synthesis of lipids that form cell membranes.

**Chlorophyll production**

Sulphur is essential to produce chlorophyll, the green pigment responsible for capturing light energy during photosynthesis (Mendili and Khadhri, 2025; Simkinet al., 2022). Chlorophyll molecules contain sulphur, which helps in the formation and stability of these pigments. Adequate sulphur ensures that plants can effectively perform photosynthesis, leading to healthy growth and development. Sulphur deficiency can result in chlorosis, characterized by yellowing leaves due to insufficient chlorophyll production, reducing the plant's ability to photosynthesize and produce energy.

**Stress response and disease resistance**

Sulphur plays a significant role in enhancing plant resilience against biotic and abiotic stresses. Sulphur-containing compounds, such as glutathione, are involved in the detoxification of reactive oxygen species (ROS), which accumulate during stress conditions like drought, salinity, and pathogen attacks (Choudhary et al., 2022). These compounds help mitigate oxidative damage, thereby protecting plant cells and improving stress tolerance. Additionally, sulphur is involved in the formation of phytoalexins, antimicrobial compounds that plants produce to defend against pathogens (Kaur et al., 2022).

**Sulphur-containing secondary metabolites**

Plants produce various secondary metabolites that contain sulphur, which contribute to their defense mechanisms and ecological interactions. Glucosinolates, a group of sulphur-containing compounds found in Brassicaceae plants, play a crucial role in deterring herbivores and pathogens. When these plants are damaged, glucosinolates are hydrolyzed to produce compounds that are toxic to pests and diseases (Scherer, 2009; Miękus et al., 2020). Similarly, alliins, found in garlic and onions, are sulphur-containing compounds with antimicrobial properties.

**Enhancing nutrient uptake and utilization**

Sulphur aids in the efficient uptake and utilization of other essential nutrients, particularly nitrogen. Adequate sulphur levels enhance the plant's ability to assimilate nitrogen into amino acids and proteins, optimizing growth and yield (Zenda et al., 2021; Dawar et al., 2023). The synergistic relationship between sulphur and nitrogen is crucial for achieving balanced nutrition and maximizing crop productivity (Carciochi et al., 2020).

**Improving crop quality and yield**

Sulphur not only influences plant health but also affects the quality and yield of crops. In cereals, sulphur improves grain quality by enhancing protein content and composition, which is vital for baking and nutritional properties (Guerrini et al., 2020; Zenda et al., 2021). In oilseed crops like canola, sulphur is essential for oil synthesis and quality (Maurya et al., 2023; Ningthi et al., 2024; Sharma et al., 2025). Adequate sulphur nutrition results in higher yields and better-quality produce, making it a critical nutrient for agricultural productivity.

Thus, Sulphur is a multifaceted nutrient essential for numerous biochemical and physiological processes in plants. Its roles in amino acid and protein synthesis, enzyme function, chlorophyll production, stress response, and disease resistance underscore its importance in plant health and productivity. Understanding and managing sulphur nutrition is crucial for optimizing crop growth, improving yield and quality, and ensuring sustainable agricultural practices.

Sulphur deficiency can compromise a plant's natural defence mechanisms, increasing its vulnerability to pests and diseases (Zenda et al., 2021; Majumdar et al., 2023). While sulfur (S) has been used as a foliar fungicide since the late 19th century, its role in enhancing disease resistance through soil application was recognized only several decades later (Bloem et al., 2005). The effectiveness of sulphur-induced resistance (SIR), measured as a reduction in disease index, has ranged from 5-50% in greenhouse trials and 17-35% in field conditions. SIR involves various metabolic pathways, including the synthesis of phytoalexins, glutathione, glucosinolates, and the emission of sulphur-containing volatiles (Haneklaus et al., 2006), highlighting sulfur's dual role in plant protection-as both a direct fungicide and indirect enhancer of disease resistance.

## SULPHUR IN SOIL

Sulphur is a critical nutrient not only for plant growth but also for maintaining soil health. Understanding the dynamics of sulphur in soil helps in managing its availability to plants and ensuring sustainable agricultural practices. This section elaborates on the sources of sulphur in soil, its cycling processes, factors affecting its bioavailability, and the role of sulphur in maintaining soil health and fertility.

### Sources of sulphur in soil

Sulphur in soil originates from several sources, including atmospheric deposition, mineral weathering, organic matter decomposition, and fertilization.

#### Atmospheric deposition

Sulphur can enter the soil through wet (rain) and dry (dust) deposition. Historically, industrial emissions contributed significantly to atmospheric sulphur, which then settled onto soils. With the reduction of sulphur emissions due to environmental regulations, atmospheric deposition has decreased, leading to lower sulphur inputs to soils (Feinberg et al., 2021; Giltrap et al., 2021).

#### Mineral weathering

Sulphur is present in soil minerals such as pyrite ($FeS_2$), gypsum ($CaSO_4 \cdot 2H_2O$), and other sulphide minerals. Weathering of these minerals releases sulphur into the soil, primarily in the form of sulphate ($SO_4^{2-}$), which is readily available for plant uptake (Lea and Azevedo, 2006; Yasin, 2024).

#### *Organic matter decomposition*

Decomposing plant and animal residues contribute organic sulphur to the soil. Microbial activity breaks down these organic materials, converting organic sulphur into inorganic forms, such as sulphate, through mineralization. This process makes sulphur available for plant uptake (Eriksen, 2009; Nivethadevi et al., 2021).

#### *Fertilization*

Application of sulphur-containing fertilizers, such as ammonium sulphate [$(NH_4)_2SO_4$] and elemental sulphur (S), is a common practice to replenish soil sulphur levels. These fertilizers provide immediate and long-term sources of sulphur, supporting crop growth and soil health (Filipek-Mazur et al., 2017; Kudi et al., 2018).

### Sulphur cycling in soil

The sulphur cycle in soil is a complex process involving various chemical and biological transformations (Fig. 2). Key processes include mineralization, immobilization, oxidation, and reduction.

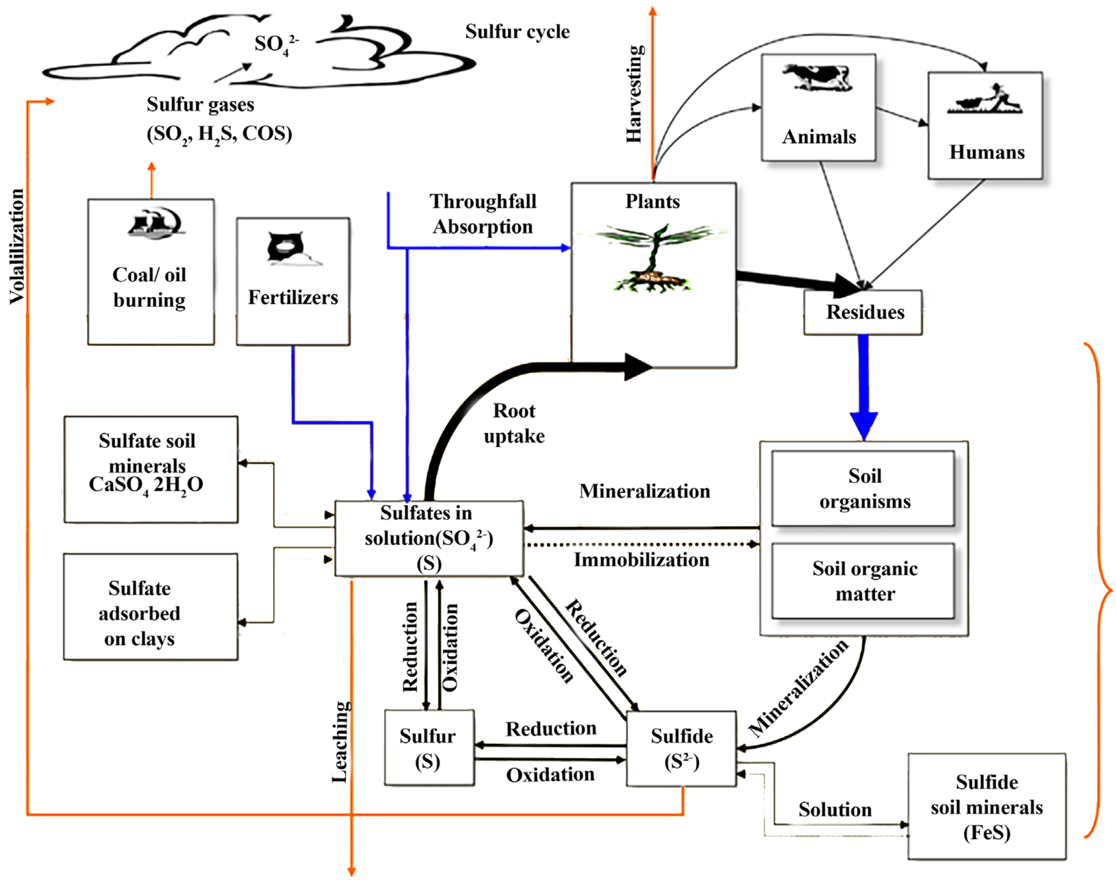


**Fig. 2.** Sulphur cycling in soil (Source: LFS:SoilWeb/Soil Biology/Nutrient Cycles/Sulfur(S) - UBC Wiki)

### *Mineralization*

Organic sulphur is converted into inorganic sulphate by soil microbes through mineralization. This process is influenced by factors such as soil temperature, moisture, and microbial activity. Mineralization is crucial for making sulphur available to plants (Gupta and Germida, 2021).

### *Immobilization*

Conversely, immobilization occurs when inorganic sulphate is assimilated by soil microbes and converted into organic forms. This temporarily removes sulphur from the pool available to plants, but it is eventually re-released through microbial turnover (Eriksen, 2009; Chaudhary et al., 2023).

### Oxidation

Elemental sulphur and sulphide minerals are oxidized to sulphate by specific soil bacteria, such as Thiobacillus species. This process is essential in soils where elemental sulphur or sulphide minerals are prevalent, as it converts these forms into plant-available sulphate (Gupta and Germida, 2021).

### Reduction

In anaerobic conditions, such as waterlogged soils, sulphate can be reduced to sulphide by anaerobic bacteria. Sulphide is toxic to plants and can lead to soil acidification. Managing soil aeration and drainage is important to prevent excessive sulphate reduction (Sarangi et al., 2022; Chaudhary et al., 2023).

### Factors affecting sulphur bioavailability

The availability of sulphur in soil is influenced by several factors, including soil pH, texture, organic matter content, and microbial activity.

***Soil pH***

Soil pH affects the solubility and mobility of sulphur compounds. In acidic soils, sulphate is more soluble and readily available to plants. However, extreme acidity can lead to leaching losses. In alkaline soils, sulphate can precipitate with calcium, reducing its availability (Malik et al., 2021; Sarangi et al., 2022).

***Soil texture***

Soil texture influences sulphur retention and movement. Sandy soils, with low organic matter and clay content, are prone to sulphate leaching. In contrast, clayey soils have higher cation exchange capacities and better sulphate retention (Grant, 2018; Yasin, 2024).

***Organic matter***

Organic matter is a reservoir of sulphur and influences its cycling and availability. Soils rich in organic matter have higher microbial activity, which enhances sulphur mineralization and availability to plants (Eriksen, 2009; Hammerschmiedt et al., 2021).

***Microbial activity***

Soil microorganisms play a crucial role in the sulphur cycle, driving processes such as mineralization, immobilization, oxidation, and reduction. Healthy microbial populations and activity levels are essential for maintaining sulphur availability (Barton et al., 2017; Zhou et al., 2025).

***Soil health and fertility***

Sulphur is integral to maintaining soil health and fertility. It contributes to the structure and stability of soil organic matter, enhances nutrient cycling, and supports the growth of beneficial soil microbes. Proper sulphur management ensures that soil remains productive and capable of sustaining high crop yields.

***Soil structure***

Sulphur helps in the formation of soil aggregates by binding organic matter and minerals. This improves soil structure, enhancing water infiltration, aeration, and root penetration (Bashir et al., 2021; Chaudhary et al., 2023).

***Nutrient cycling***

Sulphur interacts with other essential nutrients, particularly nitrogen, to enhance their uptake and utilization by plants. Balanced sulphur and nitrogen nutrition are crucial for optimizing plant growth and productivity (Zenda et al., 2021; Narayan et al., 2023).

***Microbial support***

Adequate sulphur levels support the growth and activity of beneficial soil microbes, which drive essential processes like decomposition, nutrient mineralization, and disease suppression. Healthy microbial communities contribute to overall soil fertility and resilience (Chaudhary et al., 2023; Patle et al., 2023).

Understanding the role of sulphur in soil is essential for effective nutrient management and sustainable agricultural practices. By recognizing the sources, cycling processes, and factors affecting sulphur bioavailability, farmers and soil scientists can better manage sulphur levels to ensure optimal plant growth and soil health. Advances in fertilization strategies, monitoring tools, and biotechnological approaches offer promising avenues for enhancing sulphur management, supporting sustainable crop production and environmental stewardship.

## ADVANCES IN SULPHUR RESEARCH

Research on sulphur in agriculture has seen significant advancements in recent years, driven by the need to optimize crop production and address environmental challenges. These advancements span various areas, including the development of sulphur-enriched fertilizers, the use of precision agriculture technologies, genetic improvements in crops, and enhanced understanding of soil-sulphur dynamics. This section explores these innovations and their implications for sustainable agriculture and environmental stewardship.

### Development of sulphur-enriched fertilizers

One of the most notable advancements in sulphur research is the development of sulphur-enriched fertilizers (Meena et al., 2021; Karde et al., 2024). These fertilizers are designed to provide sulphur in forms that are readily available to plants or can be converted to available forms through soil processes.

***Elemental sulphur fertilizers***

Elemental sulphur (S) is a cost-effective and concentrated source of sulphur. However, it must be oxidized by soil microbes into sulphate ($SO_4^{2-}$) before plants can use it. Advances in formulation, such as micronized or pelleted sulphur, have improved its application efficiency and oxidation rates, making it more effective in providing sulphur to crops (Shah et al., 2022).

***Sulphate-containing fertilizers***

Fertilizers that contain sulphate, such as ammonium sulphate [$(NH_4)_2SO_4$] and potassium sulphate ($K_2SO_4$), provide immediately available sulphur to plants. These fertilizers are particularly useful in situations where a rapid supply of sulphur is needed, such as during periods of peak plant demand (Eriksen, 2009; Bouranis et al., 2018).

***Enhanced efficiency fertilizers (EEFs)***

EEFs are designed to improve the availability and utilization of nutrients, including sulphur. Technologies such as controlled-release coatings and stabilized fertilizers help reduce losses and enhance nutrient uptake efficiency, providing a steady supply of sulphur throughout the growing season (Prasad and Shivay, 2021; Suman et al., 2023).

***Precision agriculture technologies***

Precision agriculture technologies have revolutionized nutrient management, including the application of sulphur. These technologies enable farmers to apply the right amount of nutrients at the right time and place, optimizing crop performance and minimizing environmental impacts (Gerson and Hinckley, 2023).

***Soil testing and mapping***

Advanced soil testing methods and geographic information systems (GIS) allow for detailed mapping of soil sulphur levels across fields. This information helps farmers identify areas with sulphur deficiencies and tailor fertilization practices, accordingly, ensuring uniform crop growth and avoiding over-application (John et al., 2021; Tagung et al., 2022).

***Variable rate technology (VRT)***

VRT uses GPS and sensor data to apply fertilizers at variable rates across a field based on soil nutrient levels and crop requirements. This technology ensures that sulphur is applied where it is most needed, improving efficiency and reducing waste (Badhai et al., 2024; Akhil et al., 2025).

***Remote sensing***

Remote sensing technologies, including satellite imagery and drones, can monitor crop health and detect signs of sulphur deficiency, such as chlorosis. These tools provide real-time data, enabling timely interventions and adjustments to fertilization practices (Mahajan et al., 2017).

**Genetic improvements in crops**

Advancements in plant genetics and biotechnology have led to the development of crop varieties with improved sulphur use efficiency and enhanced sulphur uptake.

***Genetic engineering***

Genetic engineering techniques have been used to develop crops that can better utilize available sulphur or tolerate low-sulphur conditions. For example, modifying genes involved in sulphur uptake and assimilation pathways can enhance a plant's ability to acquire and use sulphur efficiently (Hell and Wirtz, 2011; Zenda et al., 2021; Hou et al., 2023).

***Breeding programs***

Traditional breeding programs have also focused on selecting and crossbreeding crop varieties with traits that improve sulphur uptake and utilization. These programs aim to produce high-yielding, sulphur-efficient crops that perform well under varying soil sulphur conditions (Zenda et al., 2021; Dawar et al., 2023).

**Enhanced understanding of soil-sulphur dynamics**

Research has significantly advanced our understanding of how sulphur cycles in the soil and how various factors affect its availability to plants.

***Soil microbiology***

Studies on soil microbiology have shed light on the roles of different microbial communities in sulphur cycling. Understanding how these microbes mineralize organic sulphur, oxidize elemental sulphur, and reduce sulphate under anaerobic conditions helps in managing soil sulphur more effectively (Gupta and Germida, 2021; Chaudhary et al., 2023).

***Soil-plant interactions***

Research on soil-plant interactions has improved our knowledge of how plants influence and respond to sulphur availability. For example, root exudates can enhance microbial activity and sulphur mineralization, while plant root systems can be bred or engineered to explore soil sulphur more effectively (Chaudhary et al., 2023; Sharma et al., 2024).

***Environmental impact studies***

Investigations into the environmental impacts of sulphur fertilization have highlighted the importance of balanced nutrient management. Excessive sulphur application can lead to soil acidification and nutrient imbalances, while sulphur deficiency can reduce crop yields and quality. Research in this area aims to optimize sulphur use to benefit both agriculture and the environment (Liu et al., 2022; Chaudhary et al., 2023).

The advancements in sulphur research have profound implications for modern agriculture. The development of sulphur-enriched fertilizers, precision agriculture technologies, genetic improvements in crops, and enhanced understanding of soil-sulphur dynamics collectively contribute to more efficient and sustainable sulphur management. By leveraging these innovations, farmers can improve crop productivity, ensure soil health, and minimize environmental impacts, paving the way for a more resilient and sustainable agricultural future.

**Emerging technologies and methods**

In addition to traditional approaches, emerging technologies and innovative methods are shaping the future of sulphur research and its application in agriculture. These advancements focus on enhancing sulphur use efficiency, improving nutrient management practices, and minimizing environmental impacts. This section explores some of the cutting-edge technologies and methods that are revolutionizing sulphur research.

**Spectroscopy and sensor technologies**

Near-Infrared Spectroscopy (NIRS) and Mid-Infrared Spectroscopy (MIRS) are powerful tools gaining traction in sulphur research. These spectroscopic techniques analyze soil and plant samples to determine sulphur content rapidly and non-destructively. NIRS and MIRS provide real-time data, enabling precise monitoring of sulphur levels in soils and plants throughout the growing season. This information aids in timely adjustments to fertilization strategies, ensuring optimal sulphur nutrition and crop health (Soriano-Disla et al., 2019; Wei et al., 2025).

Sensor technologies, including handheld devices and integrated systems, offer on-site measurement capabilities for sulphur and other nutrients. These sensors provide farmers with immediate feedback on soil conditions, allowing for precise nutrient applications tailored to crop needs. Coupled with data analytics and remote sensing, sensor technologies contribute to efficient resource management and sustainable agriculture practices (Singh et al., 2022; Gerson and Hinckley, 2023).

**Molecular and genetic approaches**

Genomic and molecular techniques are advancing our understanding of sulphur metabolism and uptake in plants (Kopriva et al., 2015). Researchers use these approaches to identify genes and molecular pathways involved in sulphur assimilation, transport, and utilization. Genetic engineering and marker-assisted breeding programs aim to develop sulphur-efficient crop varieties that thrive under varying soil conditions. These genetically improved crops are essential for achieving higher yields and resilience to environmental stresses, contributing to food security and sustainable agriculture (Hell and Wirtz, 2011; Mangal et al., 2023).

**Nanotechnology in fertilizer development**

Nanotechnology holds promise for improving the efficiency of sulphur fertilizers. Nano-sized sulphur particles can enhance nutrient uptake by plants and reduce losses through leaching and volatilization. Nanofertilizers deliver sulphur directly to plant roots, ensuring targeted nutrient delivery and minimizing environmental impacts. Research in nanotechnology continues to explore novel formulations and delivery systems that optimize sulphur use efficiency while mitigating adverse effects on soil and water quality (Yazhini et al., 2023; Thirunavukkarasu et al., 2024; Vijayagopal et al., 2025).

**Data-driven agriculture and decision support systems**

Data-driven agriculture integrates big data analytics, machine learning, and artificial intelligence (AI) to optimize sulphur management. Advanced algorithms analyze large datasets, including soil maps, weather patterns, crop performance data, and nutrient requirements. AI-driven decision support systems provide farmers with actionable insights and predictive models for precision fertilization. These technologies enable adaptive nutrient management strategies that maximize crop productivity while minimizing input costs and environmental footprint (Reddy et al., 2024; Negrini, 2025).

**Climate-smart agriculture practices**

In the context of climate-smart agriculture, sulphur research is evolving to address the dual challenges of food security and climate change mitigation. Sustainable soil management practices, such as cover cropping, crop rotation, and organic amendments, enhance soil organic matter and microbial activity, thereby improving sulphur cycling and availability. Integrated nutrient management strategies promote efficient sulphur use, reduce greenhouse gas emissions, and enhance agricultural resilience to climate variability (Datta et al., 2022; Jariwala et al., 2022).

**Collaborative research and interdisciplinary approaches**

Collaborative research initiatives and interdisciplinary approaches are crucial for advancing sulphur research. By bringing together agronomists, soil scientists, geneticists, engineers, and environmental experts, these collaborations foster innovation and holistic solutions to complex agricultural challenges. Knowledge sharing and technology transfer across disciplines accelerate the development and adoption of sustainable sulphur management practices globally (Griffin et al., 2024; Mukherjee, 2024).

Emerging technologies and innovative methods are transforming sulphur research, offering new opportunities to enhance agricultural productivity, environmental sustainability, and food security. From spectroscopy and nanotechnology to genomic advancements and data-driven agriculture, these technologies are revolutionizing how we understand, manage, and utilize sulphur in agriculture. Continued investment in research and collaborative efforts will be essential for harnessing the full potential of these advancements and ensuring a resilient and sustainable agricultural future.

**Table 1.** Summary of key aspects in sulphur research for plant and soil health

| Sl. | Aspect of research | Summary |
|---|---|---|
| 1. | Importance of Sulphur | Essential for biochemical processes (amino acid synthesis, enzyme function, chlorophyll production), plant health (photosynthesis, stress response, disease resistance), and soil health (nutrient cycling, soil structure, microorganism activity). |
| 2. | Recent Advancements | Sulphur-enriched fertilizers, precision agriculture technologies, genetic improvements in crops, deeper understanding of soil-sulphur dynamics. |
| 3. | Technological Innovations | Spectroscopy (Near-Infrared, mid-Infrared), sensor technologies, molecular approaches, nanotechnology for improved sulphur management. |
| 4. | Genetic and Molecular Studies | Uncovering pathways for sulphur uptake and utilization, breeding sulphur-efficient crop varieties, enhancing plant resilience to fluctuating sulphur levels. |
| 5. | Data-Driven Agriculture | AI, machine learning for predictive modelling, precision farming techniques optimizing sulphur application, enhancing crop productivity and resource efficiency. |
| 6. | Sustainable Agriculture | Integration of modern techniques and strategies for sustainable practices, enhancing crop health, soil quality, and environmental management. |

## CONCLUSION

Sulphur is essential for crop growth and soil fertility, participating in protein and enzyme synthesis and sustaining soil microbes. Advances in fertilizer technology and soil testing enable more targeted and efficient sulphur application. Data-driven agriculture leverages remote sensing, soil sensors, and analytics to optimize sulphur delivery to crop needs. This precision approach improves yields and soil health while minimizing environmental impact, aligning sulphur use with sustainable farming practices. Looking forward, innovations like artificial intelligence, nano-enabled fertilizers, and genomics promise even greater efficiency in sulphur utilization, fostering resilient, productive, and environmentally sustainable agriculture.

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