

Soil Sulphur Chemistry: A Comprehensive Review on Sources, Fractions and Agricultural Significance

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ABSTRACT: Sulphur (S) is an essential macronutrient vital for plant growth, metabolism, and crop productivity. In soils, it occurs in both organic and inorganic forms, with its availability regulated by various physical, chemical, and biological processes. Growing sulphur deficiencies caused by intensive cultivation, reduced atmospheric inputs, and increased use of sulphur-free fertilizers have heightened the importance of sulphur management. This review examines the sources of sulphur in soils, including geological, atmospheric, and anthropogenic inputs, and describes the distribution, transformations, and significance of major sulphur fractions such as available, adsorbed, organic, total, and non-sulphate sulphur. Key processes governing sulphur cycling, including mineralization, immobilization, adsorption–desorption, oxidation–reduction, and plant uptake, are discussed. The review also highlights sulphur’s role in protein synthesis, enzyme activity, chlorophyll formation, nodulation, and crop quality, while summarizing analytical methods for sulphur fractionation and factors affecting its availability in different soils and agroecosystems. Current challenges and sustainable management strategies for improving sulphur use efficiency, soil fertility, and crop production are also addressed.

Keywords: *Soil sulphur fractions; Sulphur dynamics; Plant nutrition; Soil fertility; Crop productivity; Sustainable agriculture.*

Introduction

Sulphur (S) is widely recognized as the fourth major plant nutrient after nitrogen (N), phosphorus (P), and potassium (K), and it plays an indispensable role in plant growth, development, and overall productivity. It is a structural and functional component of several essential amino acids, including cysteine, cystine, and methionine, which are fundamental for protein synthesis and cellular metabolism. In addition, sulphur is a constituent of numerous enzymes, vitamins, and coenzymes that regulate key biochemical and physiological processes in plants (Tisdale et al., 1993; Stevenson, 1986). Beyond its structural role, sulphur significantly contributes to chlorophyll formation, enhancement of photosynthetic efficiency, biological nitrogen fixation, and activation of various metabolic enzymes. It also improves crop quality, particularly in oilseed and legume crops, by influencing oil content, protein quality, and flavor compounds (Gerson & Hinckley, 2023). Sulphur exists in soils in both organic and inorganic forms and undergoes continuous transformation through complex biological, chemical, and physical processes. Organic sulphur generally represents the dominant fraction of total soil sulphur, acting as a major reservoir that is gradually mineralized into plant-available forms. In contrast, sulphate (SO_4^{2-}) is the principal inorganic form absorbed directly by plants through root uptake mechanisms. The transformation and mobility of sulphur in soils are strongly governed by microbial activity, redox conditions, adsorption–desorption reactions, and leaching processes. Consequently, sulphur availability is highly dynamic and closely linked to soil properties such as pH, texture, organic matter content, and cation exchange capacity, as well as environmental and agronomic factors including rainfall patterns, temperature, and fertilizer management practices (Padhan et al., 2023; Kertesz & Mirleau, 2021). Recent studies also highlight the critical role of microbial-mediated sulphur cycling and microbial–mineral–organic matter interactions in regulating sulphur transformations and bioavailability in soils (Chaudhary et al., 2023; Zhou et al., 2025; Zhang et al., 2026).

In recent decades, sulphur deficiency has emerged as a widespread and increasingly important nutritional constraint in many agricultural ecosystems. This trend is primarily attributed to intensive cropping systems, continuous removal of nutrients through high-yielding varieties, reduced atmospheric deposition of sulphur due to environmental regulations, and the declining

use of sulphur-containing fertilizers in modern agriculture. Additionally, the increasing reliance on high-analysis fertilizers that are often sulphur-free has further exacerbated sulphur depletion in soils (Krishna, 2002; Gerson & Hinckley, 2023). As a result, understanding the sources, forms, transformations, and spatial-temporal dynamics of sulphur in soils has become essential for maintaining soil fertility, optimizing nutrient management strategies, and ensuring sustainable agricultural productivity. A comprehensive knowledge of sulphur cycling is therefore critical for developing efficient fertilizer recommendations and improving crop yield and quality under diverse agro-ecological conditions.

This review aims to provide a comprehensive overview of sulphur sources, different sulphur fractions, their distribution and transformations in soils, methods of sulphur fractionation and the significance of sulphur in crop nutrition and sustainable agricultural systems.

Soil Sulphur

Sulphur (S) is an essential macronutrient required for plant growth, development, and productivity. It plays a crucial role in protein synthesis, enzyme activation, chlorophyll formation, biological nitrogen fixation, and the production of sulfur-containing amino acids such as cysteine and methionine. In agricultural ecosystems, sulfur availability has become an increasing concern due to reduced atmospheric sulfur deposition, intensive cropping systems, the use of high-analysis sulfur-free fertilizers, and declining organic matter contents in soils. Consequently, sulfur deficiency has emerged as a widespread nutritional constraint affecting crop yield and quality in many regions of the world (Oksana *et al.*, 2024). Sulphur performs numerous physiological functions within the plant system, including protein synthesis, enzyme activation, chlorophyll formation, and the production of important amino acids and vitamins. In soils, sulphur occurs in both organic and inorganic forms, which continuously undergo various transformation processes that influence its availability to plants. The total sulphur content of soils generally ranges from 0.01% to 0.10%, although this may vary depending on soil type, parent material, climate, and management practices. Understanding the occurrence, distribution, and dynamics of sulphur is crucial for maintaining soil fertility and crop productivity. Therefore, this section provides a comprehensive discussion of the major forms of sulphur, its occurrence and behavior in agricultural soils, and the sulphur requirements of crops for sustainable agricultural production (Stevenson, 1986).

Sulphur sources in soils

Sulfur occurs in soils in both inorganic and organic forms and undergoes continuous transformation through a complex biogeochemical cycle involving mineralization, immobilization, oxidation, reduction, adsorption, and leaching processes. The predominant inorganic form available to plants is sulfate (SO_4^{2-}), whereas a major proportion of total soil sulfur is present in organic matter as sulfate esters, sulfonates, and sulfur-containing biomolecules. The balance between these pools determines sulfur availability and is strongly regulated by microbial activity, soil properties, climatic conditions, and management practices (Zhang et al., 2026). The primary sources of sulfur in agricultural soils include parent materials, atmospheric deposition, organic residues, manures, irrigation water, and sulfur-containing fertilizers. Weathering of sulfur-bearing minerals such as gypsum, pyrite, and various metal sulfides contributes to the long-term replenishment of soil sulfur reserves. Organic amendments and crop residues also constitute important sulfur inputs, particularly in soils where organic matter serves as the dominant sulfur reservoir. Recent studies emphasize that soil microorganisms play a central role in regulating sulfur transformations and controlling the release of plant-available sulfate from organic and inorganic sulfur pools (Zhou et al., 2025).

Current research further highlights the importance of sustainable sulfur management in modern agriculture. Excessive sulfur inputs may contribute to environmental problems such as soil acidification and sulfur accumulation, whereas insufficient sulfur supply can reduce nutrient use efficiency and crop productivity. Therefore, understanding the sources, forms, and cycling of sulfur in soils is fundamental for developing effective nutrient management strategies and ensuring sustainable agricultural production. The sulphur content of rocks varies considerably depending on their origin and composition. Igneous rocks generally contain between 0.02 and 0.07% sulphur, whereas sedimentary rocks contain higher amounts, ranging from 0.02 to 0.22%, making them significant contributors to soil sulphur through weathering processes. Elemental sulphur (S^0) is commonly found in volcanic deposits, salt dome formations, and geological deposits associated with calcite and gypsum. In addition, sulphur is released into the environment as gaseous compounds during volcanic eruptions and hydrothermal activities. Hydrogen sulphide (H_2S), produced through volcanic, hydrothermal, and biological processes, represents an important natural and commercial source of sulphur and is commonly present in natural gas reservoirs. Sulphur is also present in various fossil fuel resources, including crude oil, coal, and tar sands, where it occurs in organic forms. The primary origin of soil sulphur is

believed to be sulphide minerals present in parent rocks. During weathering, these minerals undergo decomposition and oxidation, converting sulphide (S^{2-}) into sulphate (SO_4^{2-}), which is the most stable and plant-available form of sulphur. The resulting sulphate may accumulate as soluble or insoluble salts in arid and semi-arid environments, become incorporated into living organisms, or be reduced back to sulphide or elemental sulphur under anaerobic conditions. A portion of the sulphate produced during mineral weathering is transported to oceans through drainage systems. Seawater contains approximately 2,700 ppm sulphate, whereas concentrations in other natural waters generally range from 0.5 to 50 ppm but may exceed 60,000 ppm in highly saline lakes and sediments (Tisdale et al., 1993).

The atmosphere represents another important source of sulphur for soils. Industrial activities and the combustion of coal and other sulphur-containing fuels release sulphur dioxide (SO_2) into the atmosphere. This atmospheric sulphur eventually returns to the soil through rainfall and dry deposition, contributing to the soil sulphur pool. Plants can also absorb SO_2 directly through leaf stomata, where it is metabolized and incorporated into plant tissues. However, excessive atmospheric SO_2 concentrations may be harmful; exposure to concentrations as low as 0.5 ppm for several hours can cause visible injury to sensitive plant species (Zhang et al., 2026).

General characteristics of soil Sulphur

Sulphur (S) is a naturally occurring element and one of the most abundant constituents of the Earth's crust. Similar to nitrogen, it is an essential nutrient required for the growth, development, and survival of all living organisms. Chemically, sulphur is a non-metallic element with the atomic number 16 and the symbol S. It is a tasteless, multivalent element that commonly occurs as a yellow crystalline solid in its elemental form. In nature, sulphur is found both as a free element and in combination with other elements as sulphide and sulphate minerals. Due to its biological significance, sulphur is regarded as an indispensable element for life and is an integral component of the amino acids cysteine and methionine, which are essential for protein synthesis. Beyond agriculture, sulphur has numerous industrial applications and is widely used in the production of fertilizers, explosives, matches, insecticides, fungicides, and various chemical products (Stevenson, 1986). The growing recognition of sulphur's importance in plant growth, crop productivity, and human and animal nutrition has stimulated extensive research on sulphur uptake, transport, assimilation, and metabolism. In plants, sulphate (SO_4^{2-}) is the principal form of sulphur absorbed from the soil and serves as the major transport and storage

form within plant tissues. Following uptake by roots, sulphate is transported to different plant organs and cellular compartments, where it undergoes assimilation into organic compounds. The movement of sulphate across cell membranes, its storage in vacuoles, and its transport to developing tissues are regulated by specialized sulphate transporter proteins that ensure an adequate supply of sulphur according to plant growth requirements. Sulphur plays a fundamental role in numerous physiological and biochemical processes. It is an essential constituent of proteins, enzymes, vitamins, coenzymes, and other sulfur-containing metabolites that regulate plant metabolism. Sulphur is also involved in chlorophyll synthesis, photosynthesis, energy transfer, and stress tolerance mechanisms. Adequate sulphur nutrition contributes to improved crop growth, yield, and quality, whereas sulphur deficiency can significantly impair plant performance. Common symptoms of sulphur deficiency include stunted growth, thin and elongated stems, chlorosis or yellowing of younger leaves, delayed maturity, and reduced seed production. Therefore, maintaining an adequate sulphur supply is critical for sustaining plant health, agricultural productivity, and nutritional quality of crops (Tisdale et al., 1993).

Status and distribution of different forms of sulphur in soils

Understanding the distribution and behavior of different forms of sulphur within the soil profile is essential for improving sulphur nutrition and enhancing crop productivity. The status of sulphur in soils varies considerably with depth and is influenced by several soil properties, including particle size distribution, soil pH, redox potential, moisture conditions, organic matter content, and the presence of free iron and aluminum oxides. In addition, physiographic factors such as topography, drainage conditions, leaching intensity, vegetation cover, and soil profile development significantly affect sulphur distribution and availability within the root zone (Tisdale et al., 1993). Sulphur exists in soils in both organic and inorganic forms, and the relative proportion of these forms differs widely depending on soil type, climatic conditions, depth, and management practices. In well-drained agricultural soils, organic sulphur generally constitutes the major fraction of total soil sulphur, whereas inorganic sulphur occurs in several distinct forms. The principal inorganic sulphur fractions include plant-available sulphur (primarily as sulphate ions, SO_4^{2-}), adsorbed sulphate retained on soil colloids, insoluble sulphates associated with calcium, barium, iron, and other elements, and reduced sulphur compounds such as sulphides that occur under anaerobic conditions. The distribution of these sulphur fractions within the soil profile and their interactions with soil properties determine the

sulphur-supplying capacity of a soil. Various transformation processes, including mineralization, immobilization, adsorption, desorption, oxidation, and reduction, regulate the release and availability of sulphur to plants. Consequently, soils differ greatly in their ability to supply sulphur depending on their physical, chemical, and biological characteristics. Factors such as organic matter content, soil texture, pH, clay mineralogy, moisture regime, and microbial activity strongly influence sulphur dynamics and contribute to the wide variation in sulphur forms observed among different soil types and agroecosystems (Kertesz and Mirleau, 2021).

Available sulphur

Available sulphur refers to the fraction of soil sulphur that can be readily absorbed and utilized by plants. It occurs predominantly as soluble sulphate (SO_4^{2-}), which is the principal form of sulphur taken up by plant roots. However, sulphate availability may decrease due to adsorption by soil particles, leaching losses, or reduction to gaseous sulphur compounds under waterlogged conditions. Environmental factors such as soil temperature, moisture content, aeration, and root distribution strongly influence sulphate uptake by plants. The contribution of subsoil sulphur to plant nutrition also varies depending on rooting depth and crop characteristics. Water-soluble sulphur, often referred to as readily available sulphur, represents only a small proportion of total soil sulphur but serves as an important indicator of the sulphur-supplying capacity of soils. In humid regions, soluble sulphate concentrations are generally below 10 ppm, although considerable variations may occur due to organic matter mineralization, sulphate leaching, crop uptake, and additions from fertilizers and irrigation water (Setia and Sharma, 2005).

Several studies have reported wide variability in water-soluble sulphur content across different soil types and agroecological regions. Reported concentrations range from as low as 1.4 ppm to over 230 ppm, depending on soil properties, climatic conditions, cropping systems, and management practices (Dwivedi et al., 1983; Balasubramaniam and Kothandaraman, 1985; Karwasra et al., 1986; Balanagoudar and Satyanarayana, 1990). In most cases, available sulphur concentrations are greater in surface soils than in subsurface horizons due to higher organic matter and biological activity near the soil surface. However, in some soils, sulphate accumulation in deeper layers may occur as a result of leaching and subsequent precipitation as gypsum or other sulphate minerals (Chaudhary et al., 2023). Available sulphur generally decreases with increasing soil depth and often constitutes only a small percentage of total soil

sulphur. Studies have shown that available sulphur typically accounts for less than 3% of total sulphur in many agricultural soils, with values varying among soil orders such as Inceptisols, Vertisols, and Alfisols. The relatively low proportion of available sulphur highlights the importance of sulphur mineralization and other transformation processes in maintaining an adequate sulphur supply for crops. Based on the critical deficiency limit of 10 mg kg⁻¹ sulphur, many agricultural soils have been reported to be deficient in plant-available sulphur, emphasizing the need for appropriate sulphur management strategies (Tandon, 1991).

Plant-available sulphur consists of three major components: (i) soluble inorganic sulphate (SO₄²⁻), (ii) adsorbed or sorbed inorganic sulphate, and (iii) the fraction of organic sulphur that becomes mineralized and available during the growing season. Together, these pools determine the sulphur nutrition status of crops and the sulphur-supplying capacity of soils.

Adsorbed sulphur

Adsorbed sulphur represents the fraction of soil sulphur retained on soil particle surfaces, mainly as sulphate ions (SO₄²⁻). This form is particularly important in acidic and highly weathered soils where sulphate is held through anion exchange reactions on positively charged surfaces of iron (Fe) and aluminum (Al) oxides and clay minerals. The adsorption capacity generally increases with decreasing soil pH, higher concentrations of Fe and Al oxides, and greater clay content. Kaolinitic clays exhibit stronger sulphate adsorption than montmorillonitic clays, whereas soil organic matter tends to reduce sulphate adsorption capacity. The accumulation of adsorbed sulphur is commonly observed in subsoil horizons, particularly in the B horizon, where sulphate leached from upper layers is retained. Highly weathered soils such as Ultisols and Oxisols often contain substantial amounts of adsorbed sulphur because of their abundance of sesquioxides and acidic nature. Although adsorbed sulphur is generally less immediately available than water-soluble sulphur, it serves as an important reserve that can gradually replenish the soil solution and support plant growth over extended periods. In some soils, adsorbed sulphur may account for up to one-third of the total sulphur content and can significantly contribute to crop sulphur nutrition, particularly when root systems extend into deeper horizons (Tisdale et al., 1993).

Sulphate sulphur is the principal form absorbed by plant roots, yet it generally constitutes less than 5% of the total soil sulphur pool. Various extraction methods, including CaCl₂, KCl, Ca(H₂PO₄)₂, and KH₂PO₄ solutions, have been developed to estimate plant-available sulphate

sulphur. Phosphate-containing extractants are effective in extracting both water-soluble and adsorbed sulphate, whereas chloride-based extractants primarily recover water-soluble sulphate. Water extraction is often considered more suitable than CaCl₂ extraction because calcium can precipitate sulphate as relatively insoluble CaSO₄ (Matula, 1999).

Several studies have demonstrated considerable variation in adsorbed sulphur content among soil types and regions. Kher and Singh (1993) reported that sulphate sulphur constituted only about 5.1% of total sulphur in mustard-growing soils of North Kashmir. Dharkanath et al. (1995) observed sulphate sulphur concentrations ranging from 17 to 240 mg kg⁻¹ in Vertisols of Maharashtra, exceeding the critical deficiency level of 10 mg kg⁻¹. Similarly, Sridhara and Ananthanarayana (1996) found that sulphate sulphur accounted for approximately 2.4% of total sulphur in rice-fallow soils of Karnataka, with concentrations decreasing with soil depth. Adsorbed sulphur contents have been reported to range from 12.9–24.8 mg kg⁻¹ in Inceptisols, 14.0–19.3 mg kg⁻¹ in Vertisols, and 49.3–59.0 mg kg⁻¹ in Alfisols. The proportion of adsorbed sulphur to total sulphur averaged 6.3%, 4.8%, and 20.1% in Inceptisols, Vertisols, and Alfisols, respectively. The relatively high adsorbed sulphur content in Alfisols is attributed to greater sulphate retention under acidic conditions and the presence of sesquioxides and kaolinitic clay minerals. Adsorbed sulphur generally shows a positive correlation with available sulphur, indicating its role as a readily replenishable sulphur reserve in soil systems (Singh *et al.*, 2000).

Organic sulphur

Organic sulphur constitutes the dominant fraction of sulphur in most well-drained agricultural soils, accounting for approximately 77–90% of total soil sulphur. Since the majority of soil sulphur exists in organic forms, this fraction serves as a major reservoir of sulphur and plays a crucial role in regulating the supply of plant-available sulphur through mineralization processes. The quantity and composition of organic sulphur largely determine the sulphur-supplying capacity of soils. Organic sulphur is generally classified into three major fractions: hydriodic acid (HI)-reducible sulphur, carbon-bonded sulphur, and residual or inert sulphur. Carbon-bonded sulphur includes sulphur-containing amino acids such as cysteine, cystine, and methionine, together with other oxidized sulphur compounds, and usually contributes 10–20% of the organic sulphur pool. The remaining 30–40% occurs as residual or inert sulphur, which is resistant to chemical reduction and remains largely unidentified (Tisdale et al., 1993). Organic matter contains approximately 0.5% sulphur and serves as the principal source of

organic sulphur compounds, including amino acids, vitamins, and other biologically important molecules. Before plants can utilize this sulphur, organic forms must undergo microbial mineralization to release sulphate ions (SO_4^{2-}). Consequently, the availability of organic sulphur depends on environmental conditions such as soil moisture, temperature, aeration, pH, and microbial activity. For this reason, organic sulphur is often regarded as an important indicator of the reserve sulphur status of soils (Kumar and Singh, 1974).

Numerous studies have demonstrated that organic sulphur content varies considerably with soil type, texture, organic matter content, climatic conditions, and management practices. Fine-textured soils generally contain higher organic sulphur concentrations than coarse-textured soils due to their greater organic matter content and retention capacity. In most soil profiles, organic sulphur decreases with increasing depth because of the corresponding decline in organic carbon. However, occasional increases in deeper horizons have been reported, possibly due to clay accumulation, organic matter illuviation, and anaerobic conditions that favor sulphur retention (Misra et al., 1990). Several investigations across India have confirmed that organic sulphur is the predominant sulphur fraction in agricultural soils. Organic sulphur has been reported to constitute 43–98% of total sulphur in soils from regions including Rajasthan, Punjab, West Bengal, Haryana, Uttar Pradesh, Bihar, Karnataka, Maharashtra, and Madhya Pradesh. Its concentration generally shows a strong positive correlation with soil organic carbon and total nitrogen, highlighting the close relationship between soil organic matter and sulphur dynamics (Singh et al., 1993; Bhatnagar et al., 2003). Overall, organic sulphur represents the largest sulphur reservoir in soils and plays a fundamental role in sustaining long-term sulphur fertility. Through gradual mineralization, it supplies sulphate to plants and contributes significantly to maintaining soil productivity and crop nutrition (Bhatnagar et al., 2003).

Release of organic sulphur

The release of sulphur in soils is closely associated with the decomposition of soil organic matter. Since a large proportion of soil sulphur exists in organic forms, mineralization serves as the primary process through which sulphur becomes available to plants. The carbon-to-sulphur (C:S) ratio of soil organic matter is generally around 100:1, although values ranging from 80:1 to 200:1 have been reported. Sulphur occurs in soil organic matter at approximately one-tenth the concentration of nitrogen, and during decomposition, sulphur is often released slightly faster than nitrogen relative to their respective abundances. As organic residues

decompose, organically bound sulphur is transformed into inorganic sulphate (SO_4^{2-}), the principal form absorbed by plants. This transformation is mediated by sulphur-oxidizing microorganisms, particularly species of the genus *Thiobacillus*, such as *Thiobacillus thiooxidans*, which oxidize reduced sulphur compounds into plant-available sulphate. The nitrogen-to-sulphur (N:S) ratio in soils generally ranges between 6.7:1 and 10:1 and is frequently used as an indicator of sulphur mineralization and nutrient balance. The quantity of sulphur released through mineralization depends on the soil organic matter content and its sulphur concentration. For example, in a soil containing 300 mg kg^{-1} total sulphur, where approximately 95% exists in organic forms, decomposition of organic matter can contribute a significant amount of plant-available sulphur annually. Assuming mineralized organic matter contains about 0.5% sulphur, approximately $3.5 \text{ mg sulphur kg}^{-1}$ soil, equivalent to nearly $7 \text{ kg ha}^{-1} \text{ year}^{-1}$, may be released through mineralization. This sulphur enters the soil sulphur cycle, supports plant growth, and subsequently becomes incorporated into newly formed organic matter. However, a portion of the released sulphate may be lost through leaching, particularly in coarse-textured soils and regions with high rainfall (Tisdale et al., 1993).

Total sulphur

Total sulphur (S) content in soils generally ranges from 0.01–0.10% and serves as an important indicator of the soil's sulphur reserve (Balik et al., 2007). Soil sulphur exists in both organic and inorganic forms, with organic matter constituting the major sulphur pool in humid regions, whereas inorganic sulphates dominate in arid and semi-arid environments. Total sulphur concentrations vary considerably depending on parent material, soil texture, organic matter content, climatic conditions, and land management practices. Reported values range from approximately 25 to over 5700 mg kg^{-1} in different soil types worldwide. In most soils, total sulphur is highest in surface horizons due to greater organic matter accumulation and decreases with depth. However, in calcareous, saline, or gypsiferous soils, sulphur may increase in subsoil layers because of sulphate and carbonate accumulation. Fine-textured soils generally contain higher total sulphur than coarse-textured soils owing to their greater capacity to retain organic matter and sulphur compounds. Numerous studies have demonstrated significant spatial and vertical variability of total sulphur across different agroecosystems, highlighting the influence of soil characteristics, climate, and vegetation on sulphur distribution and availability (Venkateswarlu et al., 1969; Balasubramaniam & Kothandaraman, 1985; Singh et al., 2000; Bhatnagar et al., 2003).

Non-sulphate sulphur form

Non-sulphate inorganic sulphur comprises sulphur associated with primary minerals, pyrite and iron polysulphides formed under waterlogged conditions, insoluble sulphates of calcium, barium, and strontium, and sulphur co-crystallized with calcium carbonate. In arid and semi-arid soils, sulphur incorporated within calcium carbonate is often the dominant form and may constitute up to 95% of total soil sulphur (Williams, 1975). Significant quantities of soluble and insoluble sulphates are commonly found in subsoil horizons, particularly where gypsum and other sulphate minerals accumulate. Numerous studies have shown that non-sulphate sulphur is a major fraction of total soil sulphur. In Indian rice-growing soils, it accounted for up to 57% of total sulphur, particularly in calcareous and alkaline soils (Venkateswarlu et al., 1969). Similar findings have been reported from Uttar Pradesh, Rajasthan, Himachal Pradesh, Haryana, Karnataka, Maharashtra, and West Bengal, where non-sulphate sulphur contributed between 25% and 98% of total sulphur depending on soil type and environmental conditions (Bhardwaj & Pathak, 1969; Sharma et al., 1988)

The distribution of non-sulphate sulphur within soil profiles is generally characterized by an increase with depth. This trend is attributed to leaching of sulphur compounds from surface layers and their subsequent accumulation in subsurface horizons, as well as the presence of calcium carbonate, iron, and aluminium compounds in deeper soil layers. Soil properties such as parent material, organic matter content, rainfall, pH, and mineral composition strongly influence the concentration and distribution of this sulphur fraction. Research across diverse agroecosystems indicates that non-sulphate sulphur frequently represents the largest sulphur pool in soils, often accounting for more than 70–90% of total sulphur. In Vertisols derived from basaltic parent materials, exceptionally high concentrations have been reported due to the abundance of iron- and aluminium-associated sulphur compounds (Dharkanath et al., 1995). Because of its dominance in many soils, the non-sulphate sulphur fraction plays an important role in determining long-term sulphur reserves and overall soil sulphur dynamics (Balanagoudar & Satyanarayana, 1990; Dharkanath et al., 1995).

Sulphur in Agricultural Soils

Sulphur exists in soils in both organic and inorganic forms and is continuously transformed between these pools. Organic sulphur occurs mainly as ester sulphates, sulphur-containing amino acids, and residual sulphur fractions. Ester sulphates generally constitute 20–65% of total

soil sulphur, while organic sulphur may account for up to 95% of total sulphur in temperate agricultural soils. Isotopic studies have demonstrated that a substantial proportion of plant-absorbed sulphur originates from this organic reserve through mineralization processes. Sulphur added to soil is commonly incorporated first into the ester sulphate fraction. Sulphur associated with amino acids is primarily contained within soil microbial biomass and decomposes rapidly, preventing significant accumulation. In contrast, residual sulphur is relatively stable and resistant to chemical hydrolysis, with its seasonal fluctuations largely controlled by biological activity in the soil (Krishna, 2002). The concentration of inorganic sulphate (SO_4^{2-}) varies widely among soils. In humid and sub-humid regions, sulphate levels are generally low because plant uptake and microbial mineralization rapidly utilize available sulphur. Conversely, tropical and subtropical soils may contain appreciable quantities of sulphate. Soils rich in gypsum, volcanic ash, or located in arid and semi-arid regions often possess substantial sulphur reserves. The distribution and availability of sulphur fractions are strongly influenced by cropping systems, vegetation cover, climatic conditions, and overall soil properties (Beaton et al., 1985)

Methods of sulphur fractions

Different extractions can be used to determine the different forms of sulphur that has been given by different scientist. Name of the different extrants are given in figure 1.

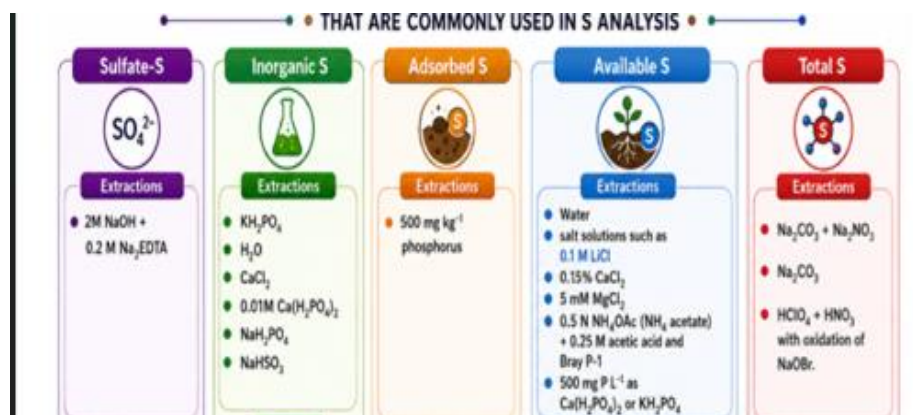


Figure 1. Methods of sulphur fractions (Ensminger, 1954)

Role of sulphur in plants

Sulphur (S) is an essential macronutrient that performs numerous physiological, biochemical, and metabolic functions in plants. Its importance in plant nutrition arises from its involvement in key biological processes that directly influence growth, development, yield, and crop quality.

Sulphur participates in respiration, energy metabolism, and the synthesis and degradation of fatty acids. It also plays a vital role in the formation of enzymes, vitamins, and other biologically active compounds required for normal plant functioning (Tisdale et al., 1993). Adequate sulphur nutrition promotes chlorophyll formation and photosynthetic activity, thereby enhancing plant growth and biomass production. It stimulates root development, seed formation, and nodule formation in leguminous crops, contributing to improved nutrient and water uptake. Sulphur also supports vigorous plant growth and is an important structural component of many enzymes and proteins involved in metabolic reactions. In oilseed crops such as mustard and soybean, sufficient sulphur supply increases oil content and improves overall product quality (Gerson & Hinckley, 2023). The significance of sulphur is particularly evident in its role as a constituent of essential sulphur-containing amino acids, including methionine, cysteine, and cystine. These amino acids are fundamental building blocks of proteins and are required for numerous cellular processes. Cystine is formed through the oxidation of two cysteine molecules and contributes to the structural stability of proteins. Sulphur is also present in several important biochemical compounds, including S-glycosides, coenzyme A, biotin, thiamine, and iron-sulphur proteins known as ferredoxins, which play critical roles in electron transport and photosynthesis. Furthermore, sulphur-containing volatile compounds such as di- and polysulphides are responsible for the characteristic flavor and pungency of crops like onion and garlic. Sulphur also enhances nodulation in leguminous plants, thereby improving biological nitrogen fixation and overall nitrogen nutrition. In addition to increasing crop yield, sulphur contributes to the production of crops with superior nutritional value, improved market quality, and enhanced resistance to environmental stresses. Therefore, an adequate supply of sulphur is essential for achieving sustainable crop productivity and maintaining high-quality agricultural produce (Tisdale *et al.*, 1993).

Sulphate ions represent the primary form of sulfur taken up by plants. However, their availability in soil, along with processes such as sorption, desorption, and diffusion, is governed by soil characteristics. In contrast, the rate at which plant roots absorb sulfur is influenced by environmental and soil conditions, including temperature, moisture content, aeration, pH, and organic matter levels. It is generally assumed that sulfur uptake from soil occurs through a combination of mass flow and diffusion mechanisms. Deficiency of sulfur typically results in stunted and thin stems, along with pale yellowing of leaves, with symptoms appearing first in younger foliage. The critical sulfur concentration varies depending on soil type, crop species,

and the plant tissue analyzed. Foliar diagnostic approaches, particularly the Diagnosis and Recommendation Integrated System (DRIS), significantly enhance the accuracy of identifying sulfur deficiency and assist in determining appropriate sulfur fertilizer requirements (Summer, 1981). Maintaining balanced nutrient ratios, especially between sulfur and other essential elements, is crucial for efficient fertilizer use (Krishna, 2002).

Kanwar and Mudhahar (1986) argued that crop sulfur requirements depend on multiple factors, some of which may still be unidentified, indicating that the system is continuously evolving. At a large scale, sulfur fertilizer demand for a country or agro-ecological zone is influenced by factors such as: (a) dominant crops and cropping patterns, (b) expected or achieved yield levels, (c) the area under different crops and their sulfur demand, and (d) cropping intensity. Generally, sulfur demand has been increasing due to higher yield targets, greater nutrient removal by crops, and the widespread use of high-analysis fertilizers lacking sulfur. On a broader scale, sulfur requirement is also linked to yield potential and nutrient-use efficiency. Several mathematical models have been developed to estimate and describe sulfur requirements. For practical purposes, Kanwar and Mudhahar (1986) categorized field crops into seven major groups, further subdividing them based on expected sulfur consumption per crop per season. They suggested that such classification can support easier policy formulation. However, sulfur requirement remains a dynamic concept influenced by soil, environmental, and crop-related factors, requiring periodic reassessment and continuous updating.

Limitations of the Review

Although this review comprehensively summarizes the sources, forms, transformations, and agricultural significance of sulphur in soils, several limitations should be acknowledged. First, much of the available literature originates from specific geographic regions, particularly India and other Asian countries, which may limit the global applicability of some findings. Second, reported values of sulphur fractions vary considerably due to differences in soil type, climate, cropping systems, analytical methods, and management practices. Third, advances in molecular biology, microbial ecology, and isotopic tracing techniques related to sulphur cycling have not been extensively covered. Finally, the review relies primarily on previously published studies and does not include new experimental data or meta-analytical assessments. Therefore, further region-specific and multidisciplinary research is required to improve understanding of sulphur dynamics under changing agricultural and environmental conditions.

Conclusion

Sulphur is an essential macronutrient that plays a vital role in plant growth, crop quality, and agricultural productivity. It exists in soils in multiple organic and inorganic forms, with their distribution and availability governed by complex biological, chemical, and environmental processes. Organic sulphur constitutes the largest fraction of total soil sulphur, while sulphate serves as the primary plant-available form. The transformation of sulphur through mineralization, immobilization, oxidation, reduction, adsorption, and desorption regulates its availability to crops. Increasing sulphur deficiency in agricultural soils highlights the need for efficient sulphur management strategies. A thorough understanding of sulphur sources, fractions, cycling processes, and assessment methods is essential for improving nutrient use efficiency, maintaining soil fertility, and sustaining crop yields. Future research should focus on developing integrated sulphur management approaches and enhancing knowledge of sulphur dynamics across diverse agroecosystems to support sustainable agriculture and global food security.

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