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# Review - Soil Sulfur Dynamics and Their Role in Plant Growth and Development

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## ABSTRACT

Sulfur (S) is an essential nutrient for plant growth, crucial for protein synthesis, enzyme function, and chlorophyll production. In acidic tropical soils, sulfur dynamics are influenced by various factors, particularly soil acidity, organic matter content, and microbial activity. This review explores the sources, transformation, availability, and cycling of Sulfur in acidic tropical soils, emphasizing its role in agriculture and ecosystem sustainability, focusing on the sources, transformation, and factors affecting sulfur availability. The weathering of minerals, especially from sulfate and sulfide minerals, contributes to the long-term supply of Sulfur in soil ecosystems. Microbial activity and soil temperature play key roles in the mineralization process of Sulfur. Plants' sulfate absorption is affected by soil conditions, including pH, texture, and organic matter content. Data indicate that acidic conditions can inhibit microbial activity, reducing sulfur availability. These findings suggest that the importance of managing sulfur availability to enhance agricultural yields in acidic tropical soils and the potential for developing microbe-based fertilizers to improve nutrient absorption efficiency by plants.

Keywords: Desorption, Distribution, Mineralization, Sulphate, Sorption, Transformation

## 1. INTRODUCTION

Sulfur (S), is an essential macronutrient required for plant physiological reactions. As a macronutrient, S is needed to compose macro and micro molecules in plant tissue. Sulfur is a component of amino acids, proteins, vitamins, and enzymes, which play an essential role in growth, development and reproduction. (Gilbert et al., 1997) (Marschner, 2012) (Eichert & Fernández, 2023). Sulfur is also found as a group of non-protein molecules, as small biomolecules containing Sulfur, including iron-sulfur clusters (Fe/S), molybdenum cofactors (Moco), and sulfur-modified nucleotides (Nakai & Maruyama-Nakashita, 2020). The study's results (Gilbert et al., 1997) showed a decrease in net assimilation of wheat leaves in plants deficient in Sulfur, which was due to low Carboxylation efficiency, which reduced Rubisco activity. Likewise, with the chlorophyll content and nitrate absorption in the plant leaves. Since S is a component of proteins, chloroplasts, and several necessary enzymes and coenzymes, S deficiency stress reduces the content of S and amino acids containing S, which causes inhibition of the synthesis of critical enzymes in the carbon metabolism process, slows the rate of photosynthesis, and results in the accumulation of more reactive oxygen species in plants (Lunde et al., 2008) (Narayan et al., 2022).

The function and role of Sulfur, Nitrogen, and Phosphorus so that most plants, especially those that produce seeds and nuts, will require as much S as P from the soil. Plants that lack Sulfur will impact the transport of Nitrogen and Phosphorus, ultimately reducing plant production. (Jamal et al., 2010) Moreover, (Sabir et al., 2015) reported that oil-producing plants require up to 300% S compared to cereal and legume plants. Effects on Other Nutrients Sulfur can also affect plants' absorption and use of other nutrients.

Although Sulfur is one of the essential nutrients for plant growth with plant requirements similar to phosphorus, this element has received little attention for many years because it is assumed that S is sufficient through atmospheric input and carrier materials from several types of fertilizers such as Kieserite. In addition, the regulation to reduce the use of S-based materials in the fertilizer and pesticide industry over the last decade has reduced S deposits in the air and soil. This affects reducing S reserves in the soil for plants. According to (R. K. Sharma et al., 2024) (Likus-Cieślik & Pietrzykowski, 2021), S deficiency is not only found in certain soils but is now a universal deficiency. The amount of S available to plants in the soil has decreased by 34–86% between 2000 and 2020, thus endangering crop production. Likewise, the study's results (Shukla et al., 2024) through PCA analysis and Fuzzy C-means algorithm (FCMA) Clustering mapped the northeastern region of India as having an S distribution of 0.22 - 99.2 mg/kg. The causes of this widespread S deficiency, according to (R. K. Sharma et al., 2024), include low industrial atmospheric deposition, stricter environmental regulations, applicable management practices such as selecting superior varieties, increasing the use of low-S fertilizers, decreasing the use of fungicides and insecticides containing S, and in some cases reduced intensity of soil cultivation.

For example, with the Clean Air Act policy by the United States Environmental Protection Agency in the 1990s and similar European laws on air emission controls, atmospheric S deposition decreased drastically. (Aas et al., 2019). (Benish et al., 2022) reported an average total deposition.

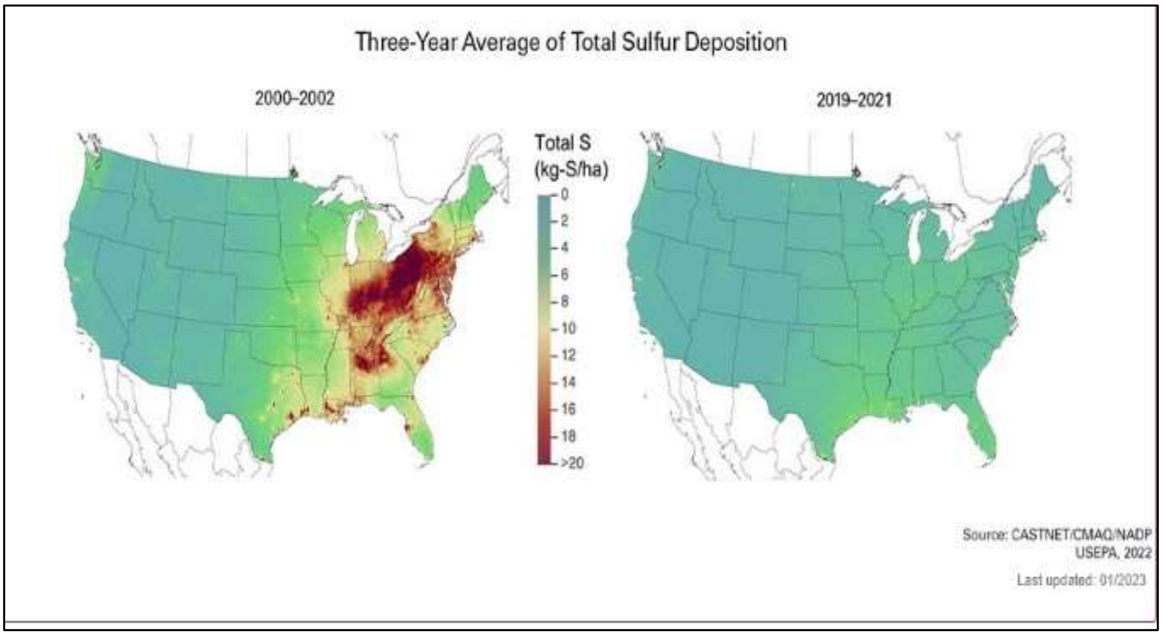

**Figure 1.** Changes in Sulfur deposition in the US mainland over three-year periods: 2000–2002 and 2018–2020.

Sulfur from 5.3 in 2002 to 1.8 kg S ha/yr. Until now, minimal mapping of the distribution of soil sulfur in Indonesia has been reported. One of them is the results of Landsat 8 satellite imagery (Darmawan, 2021) showing that the distribution of Sulfur in West Java is in areas around the volcano's peak. However, the results of this study are still limited to detecting alteration minerals related to geothermal energy in an area that has not reported quantitative data. Likewise, research (Muhammad et al., 2005) analyzed S levels based on two soil types in the South Sulawesi region, where unmeasured concentrations (tu) were found in Inceptisol and Vertisol soils. For example, fertilizer use in Malaysia and Indonesia differs significantly in terms of S supply in oil palm cultivation. In Malaysia, ammonium sulfate [$(NH_4)_2SO_4$] is the primary source of nitrogen, which, together with organic fertilizers and industrial pollution, generally ensures adequate sulfur supply. This has historically maintained adequate sulfur levels in soil and plants.

In contrast, in Indonesia, urea is the primary source of nitrogen for oil palm, and sulfur-containing fertilizers, such as single superphosphate, are rarely used; some plantations apply Kieserite, but it has not been prioritized in any land evaluation (Gerendás et al., 2014). These changes have led to a decline in the sulfur status of Indonesian soils, mainly due to sulfur uptake with harvested fruit and losses due to leaching. As a result, the sulfur status in Indonesia is reported to be marginal, with concentrations often falling below the critical levels required for optimal oil palm growth (Gerendás et al., 2014).

This review provides information on sulfur dynamics in acidic tropical soils, including its sources, transformations, and current occurrence in agricultural fields. Despite its dynamics in soils, knowledge about the extent to which S deficiency can affect plant growth and production is still limited.

## 2. SOURCES OF SULPHUR IN THE SOIL

The presence of Sulfur in the soil comes from various sources, both natural and the result of human activities. The most significant natural source of Sulfur in the soil is the weathering of minerals (Scherer, 2001), which is the soil's parent material. The decomposition of organic matter is another significant natural source of Sulfur. Soil organic matter, including decomposed plant and animal remains, generally contains about 0.5 - 3% sulfur based on its dry weight (Eriksen, 2009). Likewise, the S fraction in the soil is mainly in the form of S-organic (Uren, 1987), (Singh et al., 2005), (Jamal et al., 2010).

Atmospheric deposits have historically been a significant source of Sulfur, especially in industrial areas, fossil fuel combustion, and volcanic activity in the form of $SO_2$ gas. This atmospheric S can return to the soil through wet or dry deposition (Feinberg et al., 2021). In addition to natural sources, human activities also contribute to the presence of Sulfur in the soil. The use of sulfur-containing fertilizers is a primary anthropogenic source. Fertilizers such as ammonium sulfate, potassium sulfate, and single superphosphate directly add Sulfur to the soil. Likewise, pesticides applied in crop cultivation will leave residues in the soil (Zhao et al., 1999). Irrigation water can be a significant source of Sulfur, especially in areas with sulfur-rich aquifers. Groundwater flowing through layers of rock containing sulfur minerals can enrich itself with sulfate ions.

## 2.1 Atmospheric Precipitation

Sulfur is deposited on the soil through precipitation (Wet deposition) and dust (Dry deposition). The primary sources of atmospheric deposition include fossil fuel combustion from vehicles and electric utilities that emit Sulfur dioxide ($SO_2$) in addition to Nitrogen Oxides ($NO_x$, NO, $NO_2$) and, as well as agricultural activities that release ammonia, both of these elements (Galloway et al., 2008). After entering the atmosphere, the main pathway for sulfur (S) removal occurs through precipitation (wet deposition) or absorption of gas by surfaces, such as terrestrial and aquatic vegetation or in the form of aerosols (dry deposition). Research (Ghosh et al., 2022) in Maharashtra-India, which has a semi-arid tropical climate (hot dry) with an average annual rainfall of 721 mm, contains an S concentration of 0.6 µg mL-1. By multiplying the amount of rainfall by the S concentration in the rainwater sample, the amount of S added in the area is ~4.0 kg S $ha^{-1}$ $year^{-1}$. Rainwater samples were collected three times, namely during the first rain (June), another in the middle of the rainy season (August), and the last at the end of the rainy season (October).

Research (Benish et al., 2022) reported a large decrease in the amount of S aerosol compared to the S gas fraction in the United States in 2017. This indicates that the agricultural sector contributes to high emissions and the effect of global commitments to reduce emissions from the industrial sector and fossil combustion. According to (Behera et al., 2016), About 80% of total global emissions in 2005 were caused by agriculture, including livestock operations in the US. In tropical areas, the level of sulfur deposition in the atmosphere can be significant due to higher rainfall temperatures. The study's results (Michalovicz et al., 2021) on soil $SO_4^{2-}$ levels in 143 Ohio farms have decreased linearly by 63% from 2002 to 2014, while other chemical characters show insignificant changes. This decrease reaches a concentration range that is less for cereal crops. This decrease, according to (Benish et al., 2022) and (Michalovicz et al., 2021), is related to the decrease in emissions in the atmosphere due to the implementation of air quality regulations where $SO^{2-}$ emissions (-70%), $SO_4^{2-}$ in rainwater (- 66%), and sediment (- 52%). Likewise, research (H. Wang & Zhang, 2023) in Burnaby, Canada, from 2004 to 2018 measured S emissions in the form of SO2 gas and $SO_4^{2-}$ particulates. This study used three trend analysis methods: linear regression, Mann-Kendall test (MK-TS), and Ensemble Empirical Mode Decomposition (EEMD), where the results showed a significant reduction in the annual average concentration of $SO_2$ (59%) and $SO_4^{2-}$ (42%) during the study period. This certainly affects deposition on land and surface water.

## 2.2 Mineral Weathering

Mineralogically, Sulfur can be pure Sulfur (native Sulfur) or bound in a compound, such as sulfate minerals (gypsum, anhydrite, and barite) and sulfides (pyrite, pyrrhotite, and chalcopyrite) (Warmada & Titisari, 2015). Various types of primary and secondary minerals containing S are found in the soil, but the main ones containing S are gypsum, anhydrite, epsomite, mirabilite, pyrite, and marcasite (Chaudhary et al., 2023). These minerals slowly weather and release Sulfur into the soil. This process is generally slow but continuous, providing a long-term supply of Sulfur to the soil ecosystem. Generally, silicate minerals contain less than 0.01% S (Beegle, 2001). Sulfur can be obtained from volcanic areas and hot springs in Indonesia, Japan, Chile and Italy (Ray & Banerjee, 2016).

The parent material's mineral composition affects the soil's initial sulfur content. Igneous rocks such as pyrite ($FeS_2$) continuously increase through volcanic activity and weathering emissions of the earth's crust in the oxygen-containing atmosphere. These minerals, during weathering, release S in the form of $SO_4^{2-}$ , which is available to plants. Sulfate adsorbed on the exchange sites in the soil solution represents a source available to plants (Beegle, 2001). In the atmosphere, S is primarily present in the form of S-rich aerosols (dust) blown by the wind (Reheis & Kihl, 1995), which only last a short time in the atmosphere and then are deposited on the soil surface. Another primary source of S is the combustion of coal and other fossil fuels. Examples of soils with low S content are soils that have silicate mineral parent materials. It was reported by (Shukla et al., 2024) that 40.5% of agricultural land in India was reported to be S deficient. These lands were dominated by Vertisol soils, where these soils were dominated by Smectite (Aluminum-Silicate) minerals (Ghosh et al., 2022).

## 2.3 Organic Materials

Sulfur is present in organic and inorganic forms in soil. Organic S refers to S integrated into organic compounds, while inorganic S is present as simple ions or small molecules. More than 95% of total S in soil is present in organic form (Turbidimetry et al., 2008) due to partially decomposed plants, microorganisms, or animal residue input. Sulfur is present in organic and inorganic forms in soil. Usually, the concentration of organic S in the soil is positively correlated with organic matter. Organic S is present in two fractions, organic Sulfate and C-bonded S. Research (David et al., 1982) in podzolic soils of the Adirondack Mountains, New York, found that soil drying converted organic S threefold to sulfate in the organic horizon. The most prominent total S was in the O horizon, with 2,010 and 1,690 µg S/g in the conifer solum. Furthermore, mineral soils have maximum S concentrations in the B21 horizon, with sulfate concentrations <15% of total S in the B horizon. Organic S dominates (93% of total S) in all horizons. Carbon-bound S and sulfate esters are 74% and 18% of total S, respectively. Amino acids, especially methionine, which is included in the organic sulfate form of Sulfur in soils, have been observed to be taken up directly by plant roots (Khattab et al., 2016) (Wright, 1962).

Applying organic matter to the soil will increase microbiological biomass, including S microbes. Research (Maya Sari M. Siregar et al., 2024) and (Juliarni et al., 2021) states that many ground cover plants and organic mulch will facilitate the growth and reproduction of microbes and fungi, and this can ultimately increase the Sulfur oxidation reaction.

Proteins and amino acids are the primary forms of S in microbial cells (Banerjee & Chapman, 1996), where the microbial S value ranges from 3 to 300 µg

S per gram of dry soil weight. The samples analyzed were agricultural land, grasslands, forests and peatlands. This indicates that land use affects the number of S microbial populations. Microbial activity plays a role in the mineralization of organic Sulfur so that it is available for plant absorption. This is reinforced by the statement (Chen et al., 2022) that the rate of organic S mineralization is closely related to the EC (Electric Conductivity) value and the activity of soil microorganisms for wetlands in China. Research (Schoenau & Malhi, 2008) shows that 1 to 5% of organic Sulfur in soil with field capacity and warm water content is mineralized into Sulfate during the growing season.

Sulfur (S) constituents, microbial biomass, and sulfohydrolase activity were determined for each soil horizon at hardwood and conifer sites in Becket soil. Soil drying prior to analysis altered S constituents. There was a threefold increase ($p < 0.05$) in Sulfate in the organic horizon. Total S was greatest in the O horizon with 2,010 and 1,690 µg S/g in the conifer and hardwood solum, respectively. The mineral soil had the maximum S concentration in the B21h horizon. Sulfate concentration was a small proportion (<15%) of total S in the B horizon. Organic S was dominant (93% of total S) in all horizons. Carbon-bound S and sulfate esters were 74% and 18% of total S, respectively. Sulfate formation through mineralization may be more critical than exogenous inputs.

## 2.4 Fertilizers and Amendments

Sulfur has two crucial roles in agriculture: fertilizer and soil conditioner, especially in problematic soil conditions. As a soil conditioner, Sulfur's central role is to regulate soil pH. In alkaline soil or with a high pH, Sulfur can lower the pH by producing sulfuric acid through an oxidation process by soil microorganisms. This decrease in pH is very beneficial because, at a lower pH, essential nutrients such as phosphorus, iron, manganese, and zinc become more available to plants so that plants can grow better, Sulfur also helps improve soil structure.

**Table 1.** Source of Sulfur Fertilizer

| No | Source | S Level (%) |
|---|---|---|
| 1. | Ammonium sulfate | 24 |
| 2. | Potassium sulfate | 16–22 |
| 3. | Calcium sulfate (gypsum) | 18 |
| 4. | Calcium nitrate with Sulfur | 1–5 |
| 5. | Superphosphate, single | 12 |
| 6. | Superphosphate, double | 5 |
| 7. | Ammonium nitrate-sulfate | 5–11 |
| 8. | Ammonium sulfate liquid | 9 |
| 9. | Ammonium phosphate-sulfate | 14–20 |
| 10. | Ammonium sulfate-nitrate | 15 |
| 11 | Ammoniated superphosphate | 11–13 |
| 12. | Magnesium sulfate (Epsom salt) | 13 |
| 13. | Magnesium sulfate (Kieserite) | 10–23 |
| 14. | Potassium-magnesium sulfate | 22 |
| 15. | Potassium thiosulfate | 19–22 |
|  | Elemental Sulfur |  |
| 16. | Diammonium polyphosphate sulfur | 12–15 |
| 17. | Diammonium polyphosphate-urea phosphate-S | 100 |
| 18. | Sulfur-coated urea | 54 |
| 19. | Sulfur coated TSP | 12 |
| 20 | Rock P-S | 12 |
| 21. | Sulfur-bentonite | 10–20 |
| 22. | Iron pyrites | 12 |

Sources: (Germida & Janzen, 1993) (Narayan et al., 2022)(R. K. Sharma et al., 2024).

In problematic soils such as high salinity or sodic (high sodium) soils, Sulfur can help leach excess sodium from the soil by forming gypsum (Calcium Sulfate) when it reacts with lime. This gypsum can improve soil structure by reducing compaction and increasing soil porosity, allowing plant roots to develop better and water to be absorbed more easily. In acidic soils, Sulfur can serve as an energy source for acid-producing bacteria, which helps improve soil fertility. In addition, Sulfur helps improve soil structure by increasing the aggregation of soil particles, making it easier for plants to absorb water and nutrients.

Fertilizers containing sulfur are a common practice to increase soil sulfur levels. Organic amendments, such as compost and manure, also contribute to the sulfur content in soil. Here are some different sources of S fertilizers based on (Germida & Janzen, 1993) (Narayan et al., 2022)(R. K. Sharma et al., 2024).

Sulfur fertilization has been widely recommended by researchers such as (Aisyah et al., 2015: Egesel et al., 2009; Narayan et al., 2022 and Prasad et al., 2020) to increase the yield and quality of crops. The study's results (Muscolo et al., 2022) found that fertilization made from Sulfur + organic waste (SBO) increased the amount of potassium and Sulfate in lettuce compared to NPK and Horse Manure fertilization. Likewise, with lettuce quality parameters, secondary metabolites such as flavonoids, phenols, vitamins C and E were also higher in concentration. Antioxidant activity expressed in DPPH and TAC also increased in lettuce grown with S + SBO fertilization and other treatments. In short, lettuce was enriched in anti-inflammatory compounds and vitamins when cultivated with SBO. (Zhang et al., 2022) reported that the transfer of Cd in rice can be reduced by administering sulfate fertilizer, as evidenced by the decrease in Cd transport in grain by up to 63%. Sulfate reduces the abundance of Fe-reducing bacteria Geobacter and thus reduces the availability of Fe and Cd in the rhizosphere soil. Desulfovibrio has been shown to participate in Cd-S fixation, and its abundance is driven by sulfate, especially during flooding during rice cultivation.

## 3. TRANSFORMATION OF SULFUR IN SOIL

### 3.1 Mineralization and Immobilization

Mineralization is a biological process in which organic S contained in organic matter (such as crop residues, compost, or manure) is converted into inorganic S forms, especially Sulfate ($SO_4^{2-}$) or microbial processes convert organic Sulfur into inorganic forms so that it is available to plants. Conversely, microorganisms can immobilize S into organic forms, so it is temporarily unavailable. Research (T. Wang et al., 2023) shows that S is dissolved in the cell membrane lipids of several types of soil microbes in the form of Octa Sulfur (S8 or S valence 0) and can be transferred from the cytoplasm of one cell to another, making the old organic S fraction in the soil. Likewise (Padhan et al., 2023) stated that organic S is the dominant fraction in the soil of Mysuru, Karnataka, India, which covers 94.7% of the total soil S, while the inorganic fraction only covers 5.3%, which includes S that is soluble in water, absorbed and retained by carbonate. These data show the importance of mineralization processes in soil in order to provide S for plants.

Temperature significantly affects the mineralization process in soil. The study's results (Jaggi et al., 1999) showed that the rate of organic S mineralization in both native soil and S fertilization was greatest at a temperature of 36 °C, regardless of soil pH. Organic S mineralization of native soil (without S addition) resulted in the accumulation of 39, 66 and 47 µg $SO_4^{2-}$ – S $g^{-1}$ soil in acidic, neutral and alkaline soils in 42 days at 36 °C. Most total mineralization (62 – 74%) occurred in the first 14-day days. Of the 500 µg S0 $g^{-1}$ soil applied, 3.2–10.0%, 6.8–15.4% and 10.0–23.0%

were oxidized to $SO_4^{2-}$, and 13.4–28.6%, 16.0–29.0% and 14.6–29.0% were converted to organic S within 42 days in acidic, neutral and alkaline soils. Following the opinion of (Itanna, 2005) which states that tropical climates support S mineralization. This may be why some researchers state that tropical soils usually contain lower total S than subtropical soils, due to the high level of mineralization. This is also influenced by the soil reaction, which tends to be acidic in tropical soils. In line with research (Doruk & Sarangthem, 2022) low pH in acidic soils can affect the process of mineralization and sulfur transformation. Acidic conditions can inhibit the activity of microbes involved in the sulfur mineralization process, thereby reducing the availability of Sulfur for plants. Added by (Chen et al., 2022), the rate of organic sulfur mineralization in various wetlands (differences in flood duration) is influenced by temperature, microbial activity, and availability of organic matter.

Soil properties such as electrical conductivity (influence of salinity) and microbial activity were identified as critical factors affecting the value of organic S mineralization rate (Liu et al., 2023). A lower C/S ratio (below 200) favors the sulfur mineralization process, while a higher ratio (above 400) can cause bio-immobilization of organic Sulfur. This study (Chen et al., 2022) found that the organic S mineralization rate positively correlated with clay and silt content while showing a significant negative correlation with sand content. This suggests that soil texture and composition are important factors affecting the organic sulfur mineralization rate.

As for research (T. Wang et al., 2023) on microbes that can transfer Sulfur will be able to collaborate with plant roots to increase nutrient absorption, which can improve plant growth and resistance to environmental stress. These findings can be used to develop more efficient microbe-based fertilizers, increasing the availability of Sulfur and other nutrients to plants. This fertilizer can help increase crop yields and plant quality.

### 3.2 Oxidation and Reduction

One of the processes affecting the S biogeochemical cycle is reduction-oxidation, which occurs in the soil environment. Under aerobic conditions, Sulfur is oxidized to sulfate ($SO_4^{2-}$), the form most easily absorbed by plants. It is easily washed out and lost from the soil profile, but some are absorbed by plants and converted into organic S in plant tissue. When plants die, organic S can be decomposed into inorganic S in the soil. The results of research (Biswas et al., 2003) provided Gypsum and Potassium Sulphate fertilization on Inceptisol Soil. Sulfur from gypsum experienced leaching after 10 days of infiltration to a depth of 19-25 cm in dry soil conditions and 21-29 cm in field capacity conditions. Meanwhile, sulfur from potassium sulphate experienced 22-28 cm leaching in dry soil and 28-30 cm in field capacity soil.

Microorganisms mainly mediate the oxidation of S in soil, so the microbial community's size, composition and activity determine the oxidation rate. Because S0 oxidation is a biological process, it is greatly influenced by factors that directly affect microbial activity, including soil temperature, water potential, and aeration (Germida & Janzen, 1993). In aerobic soil, organic S will be oxidized to sulfate ($SO_4^{2-}$), carried out by microorganisms that require oxygen for respiration. For example, microorganisms of the genus

*Thiobacillus sp.* (Chaudhary et al., 2023) oxidizes sulfide (S2-) to sulfate ($SO_4^{2-}$), or the type of Bacillus anthracis oxidizes S in acidic soils (Puspitasari et al., 2014) (Agustina et al., 2020). In acidic soils with high $H^+$ solubility, this process also produces sulfuric acid ($H_2SO_4$), which can lower the soil pH further, exacerbating soil acidity conditions.

However, the process of sulfate reduction to sulfide can occur under anaerobic conditions, such as those that occur in water-saturated soils. This process is influenced by the activity of microorganisms that use Sulfate as an electron acceptor in conditions of oxygen deficiency. Under anaerobic conditions, sulfide formation can cause toxicity to plants due to the formation of compounds such as toxic $H_2S$. Conversely, sulfide oxidation can increase soil acidity, which has the potential to inhibit plant growth and reduce the availability of other essential nutrients, such as phosphorus. The biochemical cycle of S in soil is illustrated in the following figure.

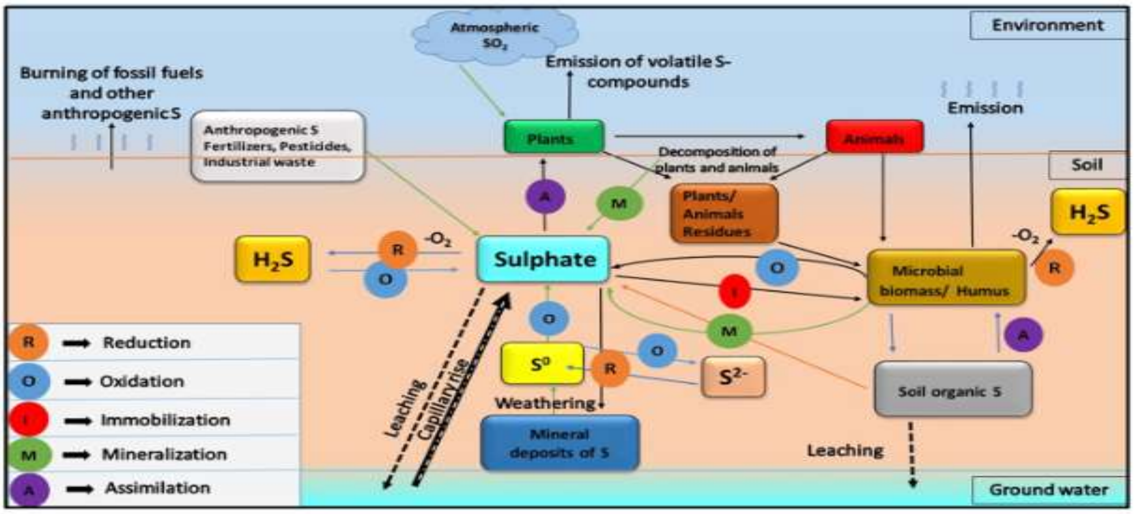

**Figure 2.** Biochemical Cycle of S in Soil. The sulfur cycle describes the processes of oxidation, reduction, mineralization, immobilization, and assimilation of Sulfur. Elemental Sulfur from mineral deposits is oxidized to sulfate, which can be assimilated by plants or microorganisms. Sulfate can also be reduced to H2S or can seep into groundwater. Fossil fuel combustion, anthropogenic S, and the addition of S-containing fertilizers (Chaudhary et al., 2023). The figure can be accessed at https://www.sciencedirect.com/science/article/pii/S0944501323000423

In water-saturated or anaerobic (oxygen-poor) acidic tropical soils, sulfate-reducing bacteria such as *Desulfovibrio sp.* (Chaudhary et al., 2023) use sulfate as an electron acceptor, reducing it to sulfide ($S^{2-}$). Sulfide can react with heavy metals such as iron, forming the mineral pyrite ($FeS_2$).

### 3.3 Adsorption and Desorption

Sulfur transformation in soil involves a series of complex biogeochemical processes. In addition to mineralization, sulfate adsorption and Desorption from soil particles also occur. Sulphate ions can be adsorbed on soil particles, especially in acidic soils with high aluminium and iron content. The desorption process releases sulfate into the soil solution, making it available for plant uptake. In addition, Sulfate can be leached, moving down the soil profile with water flow. Soil texture plays a role in Sulfur's adsorption capacity and leaching potential. Sulfur uptake in soil is mainly influenced by the physical and chemical properties of the soil, such as pH, organic matter content, clay content, and the presence of metal ions. In acidic soils, sulfate ions can be adsorbed to the surface of clay minerals and organic matter through electrostatic interactions and ligand exchange reactions. As an illustration, the dynamics of S influenced by pH are described as follows:

- In acidic soils (pH < 5.5), the soil solution contains sulfate ions ($SO_4^{2-}$) as the primary form of Sulfur.
- Positively charged hydrogen ions ($H^+$) in the soil solution are attracted to the

negatively charged sulfate ions, forming electrostatic solid bonds.

- This absorption process occurs on the surface of soil particles, especially clay and organic matter, which are negatively charged.
- The absorbed sulfate ions are tightly bound to the soil particles, reducing their availability for plant uptake.
- As the soil pH increases, the concentration of $H^+$ ions in the soil solution decreases.
- When fewer $H^+$ ions are dissolved, the electrostatic attraction between the sulfate ions and the soil particles weakens.
- This causes the absorbed sulfate ions to be released from the soil particles back into the soil solution, which is called Desorption.
- The absorbed sulfate ions are then available for plant uptake or other soil processes, such as leaching or microbial transformation.

In alkaline soils, sulfate uptake is generally lower due to increased competition with hydroxide ions ($OH^-$). In calcareous soils, calcium carbonate can affect sulfate uptake by forming calcium-sulfate mineral complexes.

On the other hand, organic sulfur compounds can be adsorbed to soil particles through various mechanisms, including hydrogen bonding, hydrophobic interactions, and cation bridging. Adsorption of organic Sulfur is typically greater in soils with higher organic matter content, as organic matter provides more surface area and functional groups for adsorption. Organic sulfur compounds can be removed from the soil through microbial decomposition and mineralization. Mineralization of organic sulfur releases inorganic Sulfate, which plants can then absorb or take up.

Soils with higher clay content generally have a greater capacity for sulfate absorption. The study's results (Biswas et al., 2003) stated that Fe2O3 and Al2O3 levels were the main factors in sulfate retention compared to pH and organic C in Inceptisol and Alfisol soils of eastern India. Likewise, the soil fraction showed a significant positive correlation with sulfate availability, where clay content of 26, 36 and 40% clay had available S of 2.4, 2.3 and 1.9 mg.kg-1, respectively. These data show values that are far from the critical limit of available S in soil, which is around 9.5 - 13.5 mg.kg-1 according to (Gourav et al., 2021) (Kalala et al., 2016) (Shelke et al., 2007). Soils with higher Fe and Al oxides and hydroxide content, such as goethite, hematite, and gibbsite, tend to have a greater capacity for sulfate absorption. According to (Mayer et al., 2001), the experiment of adding S isotopes showed a concentration of 12 kg/ha S bound by biomass, while the precipitation of Aluminum Hydroxy Sulfate minerals as the second constituent in the process of inorganic S retention in the soil.

In Desorption, several S are released back into the soil solubility to make them available to plants. The amount that returns to fill the equilibrium is also influenced by factors in the adsorption process, especially temperature and pH. The amount of S desorbed varies from 62.4 to 84.4 percent of the Sulfur absorbed. (Kour et al., 2010) Research (G. Kumar & Ranjan, 2012) states that S desorption in Indian Laterite soil averages 52.7 - 66.4% of the soil's absorption. Both of these studies were conducted in areas with a tropical climate. In contrast to the research results (A. Sharma & Sankhyan, 2020), S desorption is only around 25% of the total S absorbed by the soil in areas with a semi-tropical climate. Soil texture (clay content) significantly affects the pattern of sulfur release, and the higher the clay content, the higher the sulfur release content (Srinivasarao et al., 2004), (Kour et al., 2010), (Lavanya et al., 2019), (Minato et al., 2023) and (Doruk & Sarangthem, 2022). Research (Anggria et al., 2019) showed that the concentration of S in the washed water was higher in the treatment of rice fields without rice straw compared to those with rice straw. This indicates that straw compost prevents the release of S due to leaching.

The exchangeable and adsorbed sulfur fractions, although constituting only a tiny percentage of total soil sulfur, play an essential role in plant sulfur nutrition. In particular, in a study, these fractions contributed significantly to sorghum sulfur nutrition (Ghosh et al., 2022), accounting for 46% and 33% of sulfur uptake, respectively.

## 4. PLANT SULFUR REQUIREMENTS AND THEIR MANAGEMENT IN ACID TROPICAL SOILS

According to The Sulfur Institute, soils containing less than 10 ppm sulfur are considered low or deficient in plant-available Sulfur. Typically, cereal leaves containing less than 0.2 percent sulfur are considered deficient in Sulfur and require sulfur supplementation for optimal growth and yield. In general, plants contain 0.2–0.5% sulfur per dry matter. Optimal sulfur concentrations in growing plants are usually higher for legumes and cruciferous plants than for cereals. S deficiency, as described by (Scherer, 2001) (in Brassica plants), will be seen in young leaves (yellowing), decreased seed oil quality, and disrupted balance of Nitrogen and Phosphorus uptake. The critical concentration for visible deficiency symptoms is around 3 mg S $g^{-1}$ dry matter. Hidden deficiencies can occur at concentrations up to 6,5 mg S $g^{-1}$, which harms the formation of yield and quality without visible symptoms in plant organs. On the other hand, S fertilization increases Brassica production by 4 times in areas with low soil sulfur content and atmospheric deposition. Based on research (Gerendás et al., 2014), The critical S concentration or S:N ratio of oil palm plants is 15. Regarding this S requirement, plant tests are more recommended by (Franzen & Grant 2015) than soil tests because of the strong influence of organic matter content, landscape and soil texture factors on the availability of Sulfate. Research (Hanifah et al., 2020) S fertilization of 140kg.$H^{-1}$ significantly increased tuber diameter, fresh tuber weight and dry tuber weight by 13.39%, 140.72% and 93.64%, respectively, as well as research (Idly & Susilawati, 2023) which explains that S fertilization affects tuber quality more than leaf length growth and the number of shallots.

There is an interaction between S and N metabolism in plants, written in the review (Li et al., 2020) and (S. S. Kumar et al., 2021), that N deficiency inhibits the work of S transporters from roots to leaves. Likewise, S deficiency affects nitrate absorption and reduces nitrate reductase activity, which causes nitrate accumulation and decreased N utilization in plants. S deficiency stress causes a decrease in S content and S-containing amino acids in plants, which can be the cause of inhibited protein synthesis and accumulation of non-protein N forms. S absorption and metabolism are also affected by C metabolism in plants. Sugar can increase the expression of S transporters and increase the activity and transcription level of adenosine 5′ -phosphosulfate reductase. Under $CO^{2-}$ free conditions, S absorption and transport are inhibited, while plants' APR activity and transcription levels decrease. Correlation between S and P nutrient metabolism in plants Sulpholipids are rapidly synthesized to replace phospholipids under P deficiency conditions, and phospholipids can also replace sulfolipids under S deficiency conditions (Narayan et al., 2022).

Research (Franzen & Grant, 2015) showed that sulfur deficiency significantly reduced Canola crop yields by up to 30%. Applying sulfur fertilizer at a rate of 20-40 kg/ha increases seed yield, oil, and protein. The study found that sulfur application also improved plant health by increasing resistance to fungal diseases, especially Sclerotinia. (Poisson et al., 2019). Likewise, research (Ma et al., 2021) shows that sulfur application significantly increased aboveground biomass, grain yield, and soil water content at a 30–120 cm soil depth while reducing corn plants' water consumption and nitrogen uptake efficiency. Research (Y. Wang et al., 2023) added that Ammonium Sulphate fertilization increased corn yields by up to 24.3%. In addition, S fertilization can reduce the population of soil organisms that dominate the ecosystem. Research (Alemu et al., 2023) in Munessaworeda, Arsi zone of Oromia Regional State, Ethiopia, with clay soil type and rainfall of 900-1200 mm, the effect of S fertilizer at a dose of 45 kg.ha$^{-1}$ increased wheat grain yield by 14% compared to without the addition of S.(Briat et al., 2020)

Although plant leaves can absorb $SO_2$ and $H_2S$ in gaseous form, the main source of S available to plants is Sulfate ($SO_4^{2-}$) in the soil. Plant roots actively absorb $SO_4^{2-}$ and transport it to the aboveground part via the xylem. Most of the $SO_4^{2-}$ is assimilated into reduced organic S in the plastids (especially in the chloroplasts), while excess $SO_4^{2-}$ is transported to the vacuole for storage (Chan et al., 2019). There are several ways to overcome sulfur deficiency. Chemical fertilizers, manure, compost, or organic matter can be used to overcome sulfur deficiency. Types of fertilizers containing Sulfur (Table 1) that are commercially available and can be directly absorbed by plants. Ammonium thiosulfate is used with urea ammonium nitrate solution or a mixture of ammonium sulfate and urea. However, the provision of S fertilizer must consider the time of need of the plant. According to The Sulfur Institute, plants utilize 40-60% of S during the flowering and pod-filling periods. The role of Arbuscular Mycorrhizal Fungi (AMF) in providing AMF sulfur can be considered. AMF acts as a biofertilizer that enhances plant growth by increasing the absorption of water and mineral nutrients from the soil rhizosphere. Intra-radicular hyphae (IH) of AMF offer fungal expansion within the cortical region of the host plant.

In contrast, extra-radicular hyphae (ERH) have three main functions: host plant infection, nutrient acquisition, and fertile spore production. In S-poor soils, these ERH of AMF can enlarge and extend across the $SO_4^{2-}$ depletion region and can be a major contributing factor in the provision. AMF hyphae provide a large surface area compared to plant roots, which act as an important site for microbial interactions that play an essential role in nutrient cycling. It has been shown that root endophytic fungi such as AMF Serendipita indica help maize plants absorb Sulfate, especially under sulfur-deficient conditions (Narayan et al., 2022). An important thing to apply in S fertilization is the character of this element, which is readily leached and requires the addition of organic matter.

Based on these S dynamics, management should focus on increasing the availability and efficiency of Sulfur for plants through approaches that support the natural sulfur cycle in the soil. Using microorganisms such as Thiobacillus for sulfur oxidation helps plants absorb Sulfur efficiently. Monitoring Sulfur Levels by conducting sulfur tests on soil and plants to detect early deficiencies is recommended regularly.

This approach supports the natural sulfur cycle and improves the productivity of acid soils by optimizing the role of Sulfur for plant growth.

## 5. CONCLUSION

Sulphur (S) is an essential nutrient for plant growth in acid tropical soils, but its availability is affected by soil acidity, organic matter and microbial activity. Weathering sulphate and sulphide minerals provide long-term sulphur, but acidic conditions can inhibit microbes that favour sulphur availability. Therefore, sulphur management through fertilizers, organic amendments and sustainable farming practices is essential to improve agricultural yields. Further research on microbial-based fertilizers may also improve the efficiency of plants' nutrient uptake.

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