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Sulfur Cycling in Soils: The Role of Organic Matter

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Sulfur is an essential plant nutrient vital for protein, vitamin and coenzyme synthesis, chlorophyll formation, stress tolerance and overall crop productivity. In soils, it exists in organic and inorganic forms and cycles continuously, largely regulated by soil organic matter. Organic-rich horizons act as both a reservoir and sink of sulfur, controlling its chemical forms, mobility and plant availability. Microorganisms drive these transformations through mineralization and immobilization, while soil conditions and management practices influence sulfur cycling. Enhancing organic matter through compost, residue retention and conservation agriculture supports microbial activity and sustainable sulfur supply. Understanding these processes is key to maintaining soil fertility, crop productivity and environmentally sound soil management.

Keywords: Sulfur, Soil Organic Matter, Microbial transformation

Introduction

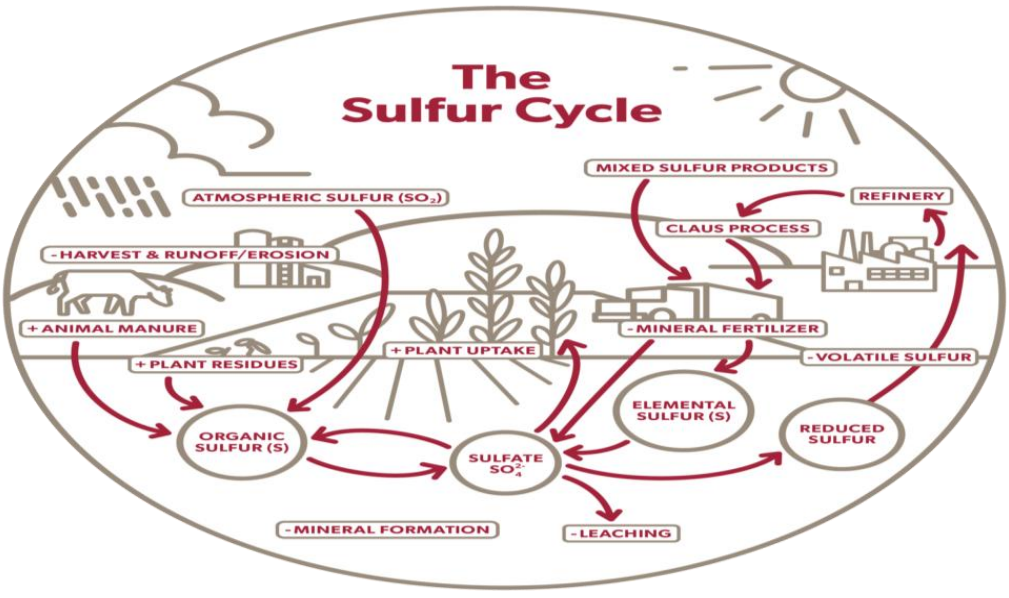
Sulfur is an essential plant nutrient that plays a key role in protein synthesis, enzyme activity and overall crop productivity. In soils, sulfur occurs in multiple chemical forms and is continuously transformed through the sulfur cycle, a dynamic process largely regulated by soil organic matter. Organic-rich surface soil horizons play a crucial role in the global sulfur cycle, as soil organic matter serves as both a major source and sink of sulfur. Its composition and geochemical environment strongly influence sulfur speciation and mobility in soils, thereby controlling the release of plant-available sulfur forms. Depending on its chemical form, sulfur can also be highly reactive, influencing metal pollutant mobility and the availability of nutrient cations in soil systems (Schroth *et al.*, 2007). Sulfur transformations in soils, including mineralization, oxidation and reduction, are strongly influenced by the quantity and quality of organic matter. Enhancing soil organic matter can improve the retention and gradual release of plant-available sulfur, supporting crop nutrition. Moreover, organic matter-mediated sulfur cycling contributes to soil health by regulating nutrient interactions and mitigating the mobility of potentially toxic elements. Understanding the role of organic matter in sulfur cycling is therefore essential for maintaining soil fertility and sustaining agricultural productivity.

Forms of Sulfur in Soils

- Sulfur in soils exists in **two main forms**: **organic** and **inorganic**.
- **Inorganic sulfur** is mainly present as **sulfate (SO_4^{2-})**, which is directly **available to plant.**
- **Organic sulfur** makes up **over 90% of total soil sulfur** in most agricultural soils.
- Organic sulfur is bound within soil organic matter**,** including plant residues, microbial biomass and humus. This organic sulfur is not immediately available to plants and must be converted into inorganic forms through biological processes **s**uch as microbial mineralization.

The Sulfur Cycle

1) **Sulfur in rocks and minerals:** Most of Earth's sulfur is stored in the Earth's crust as sulfide and sulfate minerals. It remains trapped for millions of years, forming the largest natural sulfur reservoir and is not directly available to living organisms.
2) **Weathering and release of sulfur:** Through natural weathering of rocks by rain, wind and temperature changes, S is gradually released into the environment. It enters the soil and water bodies mainly as SO_4^{2-}, which dissolve in water and become available for plants.
3) **Sulfur entering the atmosphere:** Sulfur is released into the atmosphere through natural events such as volcanic eruptions, decay of organic matter and emissions from oceans. Human activities like burning coal, oil and natural gas also release large amounts of sulfur dioxide into the air. These gases play an important role in atmospheric chemical reactions.
4) **Formation of acid rain:** In the atmosphere, sulfur dioxide reacts with oxygen and water vapor to form sulfuric acid. This acid mixes with rainwater and falls back to the Earth as acid rain. Acid rain can harm plants, soil, buildings and aquatic ecosystems.
5) **Absorption by plants:** Plants absorb sulfur from the soil through their roots mainly in the form of sulfate ions. Sulfur is an essential make proteins, enzymes and vitamins.
6) **Transfer through the food chain:** Animals obtain sulfur by eating plants or by consuming other animals. Sulfur becomes part of animal body tissues such as muscles, hair, skin and feathers. In this way, sulfur moves through the food chain from producers to consumers.
7) **Decomposition process:** When plants and animals die, decomposers like bacteria and fungi break down their bodies and sulfur compounds are released back into the soil and atmosphere.
8) **Sedimentation and long-term storage:** Some sulfur is transported into rivers, lakes, and oceans, where it settles as sediments. Over long periods, these sediments form sulfur-containing rocks, storing sulfur until it is released again through weathering.



(The Sulfur Cycle)

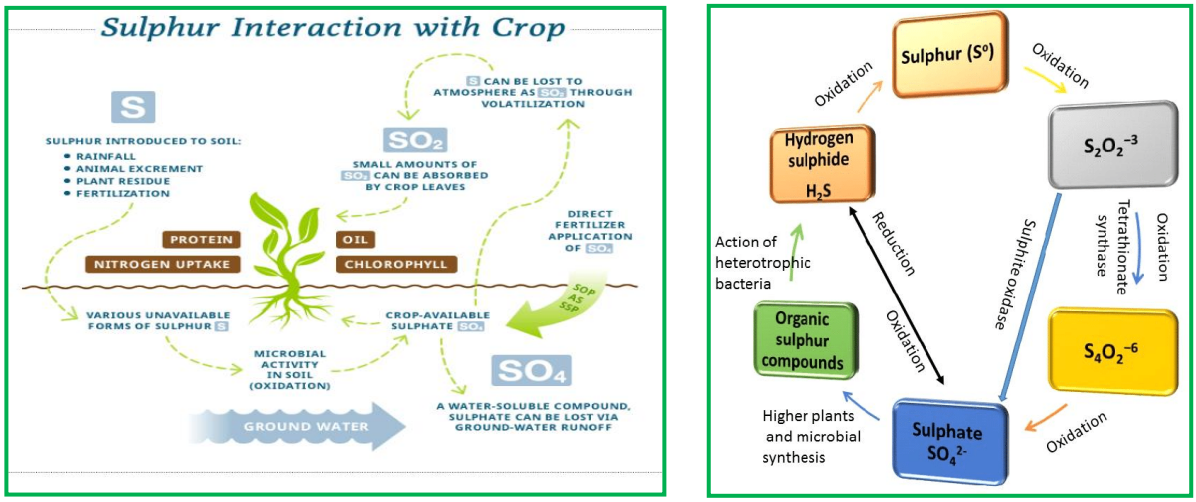
The Central Role of Organic Matter

1. A Major Sulfur Reservoir: Soil organic matter holds most of the sulfur in soil ecosystems. This large pool acts as both a source and sink of sulfur, releasing it slowly over time as organic matter decomposes.

2. Influencing Sulfur Speciation: The chemical makeup of organic matter determines which sulfur compounds are present, how stable they are and how easily they can be transformed.

For example, intermediate organic forms like sulfoxides and sulfonates change during decomposition, often becoming more available as sulfate.

3. Enhancing Soil Fertility: Organic matter improves soil structure, water retention and aeration conditions that support a rich community of microbes vital for sulfur cycling. Fields managed with practices that build organic matter, like conservation agriculture (minimal tillage and crop residue retention), often show increased sulfur pools and improved nutrient cycling.



(Sulfur interaction with crop and its transformation)

Microbial Transformations and Sulfur Availability

- ✓ Microorganisms are the engine of sulfur cycling. Bacteria and fungi transform organic sulfur into inorganic sulfate through mineralization. At the same time, they can assimilate sulfate into organic forms during growth-a process called **immobilization**. (Chaudhary *et al.*, 2023)
- ✓ Some soil microbes like, **sulfur-oxidizing bacteria** (such as *Thiobacillus* spp.) also **oxidize reduced sulfur compounds**, such as elemental sulfur or sulfides, into sulfate-a form plants can use directly. Others perform **sulfur reduction** during anaerobic processes, which can produce sulfide in low-oxygen environments.
- ✓ Research is increasingly showing that these microbial transformations vary with soil type, moisture, temperature, O.M. content and that specific microbial communities with the genetic ability to cycle sulfur are widespread even in deep soil layers. (Patsis *et al.* 2025).

Factors Affecting Sulfur Transformation

- ❖ **Soil pH:** Neutral to slightly acidic soils favor S oxidation and increase sulfate availability.
- ❖ **Soil texture and aeration:** Well-aerated soils with good structure enhance microbial activity and sulfur cycling, while compacted soils slow sulfur transformation.
- ❖ **Organic amendments:** Application of FYM, compost or crop residues increases microbial biomass and arylsulfatase activity, promoting mineralization of organic S into sulfate.

Interactions with Soil Fertility and the Environment

- Sulfur cycling interacts with nitrogen and carbon cycles, influences nutrient retention and affects pollutant mobility. Organic sulfur compounds can bind metals, altering their movement and availability to plants.
- Sulfur from fertilizers, organic amendments and atmospheric deposition influences sulfur cycling. Reduced atmospheric sulfur deposition has increased the importance of soil organic matter as a major source of plant-available sulfur in cropping systems.

Major sulfur inputs to soil from plant litter and animal residues are shown by **blue lines**, representing the addition of mainly organic sulfur. Microbial transformations between organic sulfur pools and mineralization or immobilization of sulfur are indicated by **green**

lines, with line thickness reflecting dominant pathways. Breakdown of complex sulfonates involving fungal depolymerization is shown by **dotted purple lines**. Transfer of mineralized sulfur to plants via mycorrhizal fungal pathways is represented by **dashed gray lines**. The release of inorganic sulfate through microbial turnover, autolysis and grazing by soil microfauna, leading to plant uptake, is indicated by **red lines**.

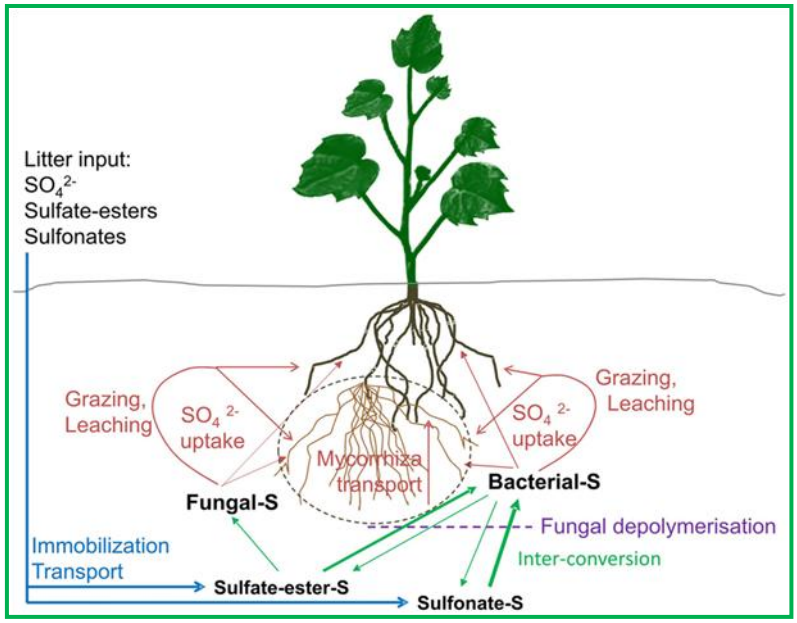


Illustration of the sulfur cycle in soil with plant cover

Management Practices for Enhancing Sulfur Cycling

- **Increase organic matter** through compost, manure and crop residues, which boosts both organic sulfur and overall soil health.
- **Use conservation agriculture practices** (reduced tillage, residue retention) to build organic pools and support sulfur transformations.
- **Promote microbial diversity** by avoiding excessive chemical inputs and supporting soil biological activity, which enhances sulfur mineralization and plant nutrient availability.

Conclusion

The sulfur cycle in soils is a dynamic interplay of chemical and biological processes that depends heavily on **soil organic matter**. Organic matter acts as a **major reservoir of sulfur**, governing how it is stored, transformed and made available to plants. Soil microorganisms are the catalysts of these transformations. Soil management practices that build organic matter improve sulfur cycling, soil fertility and sustainable crop production. As global agricultural systems face nutrient depletion and environmental challenges, understanding and enhancing sulfur cycling through organic matter conservation must be part of the solution.

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