

Soil and Fertilizer Sulfur

By Robert Mikkelsen and Robert Norton

A continual supply of sulfur (S) is essential for plant growth. Organic matter is the largest reservoir of S in soil, but it must be converted to soluble sulfate before plants can take it up. The major source of S fertilizer is obtained from scrubbing fossil fuels. There are many excellent soluble and slowly soluble sources of S fertilizer that can meet plant nutritional requirements when applied at the right rate, time and place.

Sulfur is widely distributed in nature and essential for the health of both plants and animals. It often accumulates in areas with volcanic activity, and large geologic deposits of elemental S are scattered across the world. Volcanic S and pyrite (Fe_2S) were the primary sources of S until recently. In the 20th century, the Frasch process of melting S in underground deposits was developed, making S more accessible for agricultural and industrial purposes.

Fossil hydrocarbons contain S since it was present in the organic material that formed them. This fossil S is now recovered as a by-product from materials such as oil, methane, oil sands, and coal. Sulfur removal also reduces air pollution during combustion of the fossil fuel. Elemental S is currently extracted wherever oil or gas is processed and refined. Sulfur is traded globally in a solid or in a molten form.

Sulfur is an important product in many industrial processes, especially as sulfuric acid. The production of phosphate fertilizer is the single largest use of S. The global supply and price of S is closely linked with the phosphate fertilizer market.

Sulfur in the Soil

Organic S

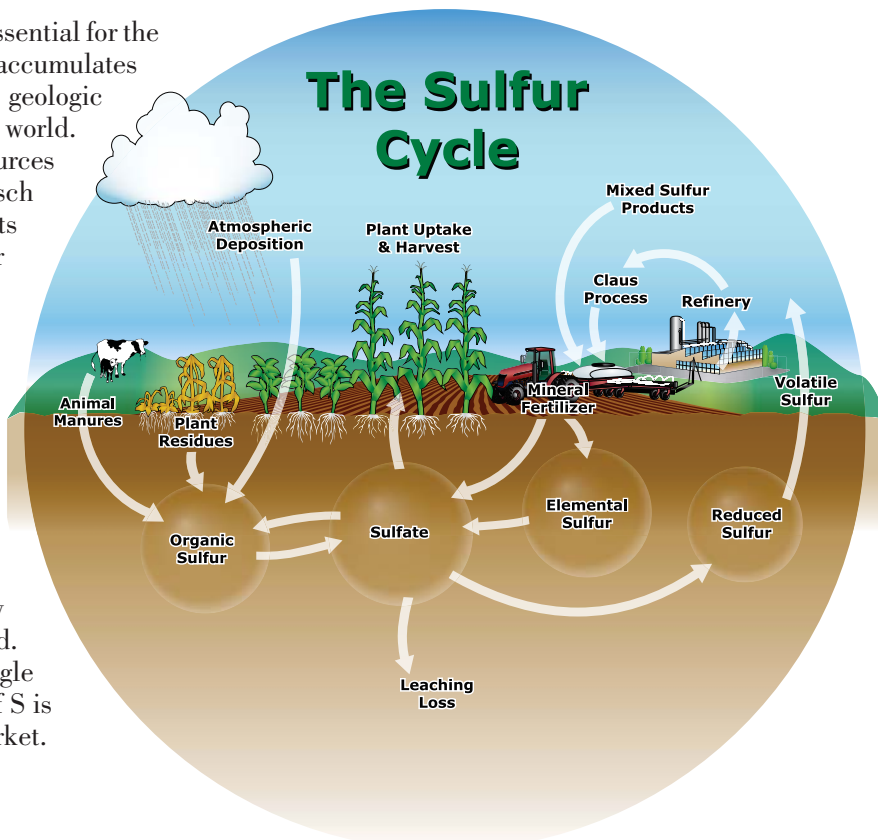
The majority of S in soil is present as organic compounds found in crop residues and soil organic matter (up to 98% of the total S). There is a variety of complex S-containing compounds in organic matter (such as ester sulfates and carbon-bonded S) but plant roots are not able to assimilate these forms until they are first converted into soluble sulfate by microbial action.

Sulfur in the soil is continually transformed between organic and inorganic compounds by microbial action. Mineralization occurs when sulfate is released as a by-product of microbial activity. Immobilization results when sulfate is incorporated into microbes during their growth.

One simple technique for predicting whether net mineralization or immobilization will occur is to measure the ratio of carbon (C) and S in the soil. Sulfate is generally released when the C:S ratio of organic matter is lower than 200:1 and immobilization typically occurs when the C:S ratio exceeds 400:1. When the C:S ratio is between these two benchmarks, the fate of S is less predictable.

Sulfur mineralization from soil organic matter is often too slow to meet the nutritional demands of high-yielding crops. This nutrient deficit must be overcome with supplementation from mineral or organic fertilizers.

Abbreviations and notes: N = nitrogen; P = phosphorus; S = sulfur; Fe = iron; Mn = manganese; Zn = zinc; ppm = parts per million.



Inorganic S

Only a small fraction of the total S in soil is found as inorganic compounds. Sulfate is the most abundant form of inorganic S in soil. It is found dissolved in water, retained on the surface of soil minerals, or in minerals such as gypsum. In wetlands and poorly-drained soil, sulfide minerals (such as pyrite) can accumulate.

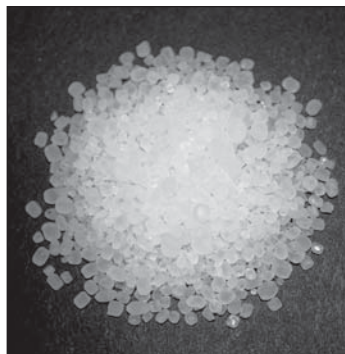
Sulfate is generally soluble and moves with soil water. It is only weakly retained (adsorbed) by a variety of clays and soil minerals, especially in low-pH conditions. Soil-adsorbed sulfate can represent an important reservoir of nutrition for plants, especially in acidic subsoils. Specific adsorption of sulfate also occurs in some soils, especially those with high levels of free Fe and aluminum oxides and hydroxides. The extent of non-specific sulfate adsorption is reduced by liming and by adding phosphate fertilizer.

Sulfate leaching

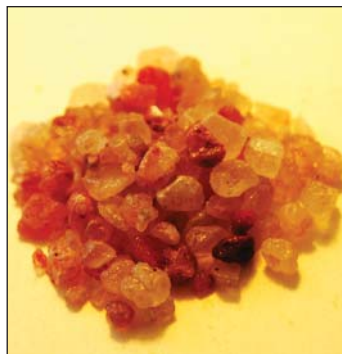
Sulfate leaching from the root zone with rainfall or irrigation water can be a major pathway of loss. The magnitude of sulfate loss through leaching will vary depending on the soil and environmental factors, but annual losses are often in the range of 5 to 60 kg S/ha (4 to 54 lb/A). Sulfate leaching is generally



Elemental S



Ammonium Sulfate



Langbeinite



Potassium Sulfate

lower from soils with vigorously growing crops compared with unplanted soils. Cover crops are commonly used to minimize nitrate-leaching losses, but they can also help with the recovery and recycling of sulfate that may also be at risk of loss.

Volatilization

In anaerobic soil conditions, sulfate is chemically reduced by bacteria to a variety of compounds that are largely unavailable for plant uptake. These include carbon disulfide, carbonyl sulfide, dimethyl disulfide, methyl mercaptan, and volatile hydrogen sulfide gas. Sulfide compounds commonly react with Fe to form pyrite minerals.

Atmospheric S

Sulfur dioxide (SO₂) is one of a group of highly reactive gases that are emitted during fossil fuel combustion. Since SO₂ emissions are linked to respiratory damage and acid rain, government restrictions limit its release. Much of the S contained in fossil fuel (especially hydrogen sulfide) is scrubbed prior to combustion, providing the major source of commercially available S.

Environmental Considerations

There are no government limits on sulfate in drinking water, but the U.S. Environmental Protection Agency suggests a limit of 250 mg/L due to taste and odor concerns. When hydrogen sulfide is found in well water, only a few mg/L (ppm) can result in poor taste and odor. In surface water, sulfate is rarely a limiting nutrient for stimulating aquatic organisms, but it can be involved in secondary reactions.

Sulfur as a Plant Nutrient

Harvesting crops from a field can gradually deplete the soil reservoir of S if it is not replaced. Soils with a large organic reserve may not require supplemental S, but many soils and crops benefit from regular additions of S.

Soil and Tissue Testing

A variety of soil testing tools have been developed to predict the availability of S for plants. These tests have been more successful in some regions than others. Since estimating plant-available S is partially dependent on mineralization of soil organic matter, soil testing has met with mixed success in making predictions. Plant growth responses to S fertilizer are most common in coarse-textured soils with low organic matter content, but positive responses to added S are observed in many areas of the world.

Because sulfate is mobile in soil, it can accumulate at depths below the topsoil. Soil samples for S analysis should

reflect the full root depth to account for S below the surface layer. The inclusion of deeper soil layers in the analysis will often improve the predictability of soil S tests, particularly on coarse-textured soils.

Plant tissue analysis has been a reliable tool for evaluating the need for additional S. The specific plant part that is analyzed and the time of sampling will vary for each crop species, but generally it involves analysis of young plant parts during a period of high S demand. The caution here is that where nutrient stratification occurs, S located deeper in the soil will not be accessible until roots reach this depth.

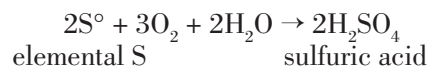
Sources of Sulfur for Plant Nutrition

If diagnostic tools suggest a need for additional S, there are many excellent sources of S that can be used to supplement the soil supply.

Elemental Sulfur (99% S): Elemental S is insoluble and requires microbial oxidation to sulfate before plants can take it up. The rate of oxidation is largely governed by the properties of the elemental S and various soil environmental conditions.

The surface area per unit of mass of S granules is inversely proportional to the particle size. Very small particles are oxidized more rapidly by soil bacteria than large particles since there is more surface area. However fine S particles are difficult to uniformly apply and air-borne S dust can present a fire hazard and a respiratory irritant, making it impractical as a common fertilizer. Maximizing the particle surface area exposed to soil speeds the conversion of elemental S to sulfate, so mixing S with the soil is generally preferred over a band application.

Elemental S is oxidized by various soil microorganisms, especially by the genus *Thiobacilli* (*Acidithiobacillus*). When conditions of soil temperature, moisture, pH, and aeration are favorable for microbial growth, S oxidation will be much more rapid than in cool and dry conditions.

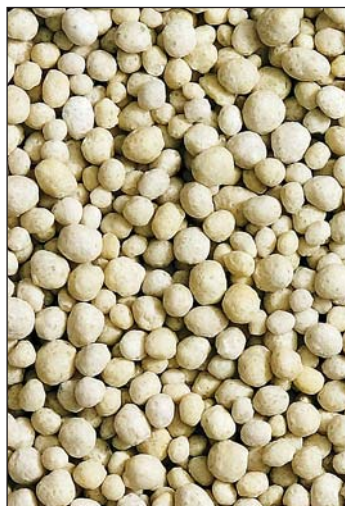


Elemental S is also used as a source of acid to lower the pH of soils and water. A common approximation is that 1 t of elemental S will neutralize 3 t of limestone. It also has a long history as a fungicide.

Clay-amended Sulfur (90% S): Molten S is mixed with approximately 10% bentonite clay to form a pellet (or pastille). When the clay becomes wet in the soil, it swells and breaks the pellet into many small pieces with a very large reactive surface area. Many clay-amended S products are amended with



Potassium Thiosulfate



Kieserite



Gypsum



Single Superphosphate

various micronutrients (including Zn, Fe and Mn) that may benefit from the acidity produced during S oxidation.

Gypsum (16 to 18% S): Calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is only slightly soluble in water (0.2 g/L) and provides sulfate for plant nutrition as it slowly dissolves. Additionally, gypsum is used as a calcium source where it is lacking and also in the reclamation of sodic soils.

Single Superphosphate (11 to 12% S): This fertilizer is made by reacting sulfuric acid with rock phosphate to produce a mixture of monocalcium phosphate and gypsum. The popularity of this fertilizer has declined because more concentrated forms of P fertilizers are less expensive to transport and handle.

Ammonium Sulfate (24% S): Ammonium sulfate $[(\text{NH}_4)_2\text{SO}_4]$ is a commonly used fertilizer to supply both N and S. Most of this fertilizer is produced as a by-product from various industrial processes, although it is sometimes made by the reaction of ammonia and sulfuric acid. Ammonium sulfate is very soluble and frequently used in fluid fertilizers. The soil acidification that occurs following application of $(\text{NH}_4)_2\text{SO}_4$ arises during the nitrification of ammonium (to nitric acid), rather than from the sulfate that is applied.

Potassium Sulfate (17 to 18% S): This common fertilizer $[\text{K}_2\text{SO}_4]$ can be recovered directly from saltwater brines or produced by reaction of various minerals and acids. It is very soluble and makes an excellent source of sulfate for plants.

Potassium Magnesium Sulfate (Langbeinite) (20 to 22% S): The langbeinite mineral $(\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4)$ is extracted from geologic sources and provides a soluble source of three essential plant nutrients. It is highly soluble.

Ammonium Nitrate Sulfate (6 to 14% S): This material is formed by reaction of nitric and sulfuric acid neutralized with ammonia. The S content will vary depending on the reaction products. More recently, a new fertilizer is available that results from fusing ammonium nitrate and ammonium sulfate

into a single granule (14% S).

Sulfur-enriched Fertilizer: Common fertilizers (such as monoammonium phosphate or diammonium phosphate) are sometimes amended with a mixture of fine particles of elemental S and soluble sulfate to provide an immediate and extended release of S. The acidity that develops surrounding the elemental S can be beneficial in maintaining the solubility of nutrients such as P and Zn.

Thiosulfate (10 to 26% S): Thiosulfate fertilizers are clear liquids that contain S in the form of $\text{S}_2\text{O}_3^{2-}$. These fluids are commonly mixed with other fertilizer solutions. In the soil, thiosulfate is converted to sulfate within a week or two in warm conditions.

Magnesium Sulfate (14 to 22% S): Two common sources of this material include the minerals kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) and Epsom salt ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$). These materials are quite soluble and provide a readily available source of sulfate.

Manure and Compost: The S content of manures and composts is quite variable depending on the animal species, diet and handling. On a dry weight basis, the S content of manures and composts generally ranges between 0.3 and 1%. A period of mineralization is required to convert organic S-containing compounds to sulfate prior to plant uptake.

The selection of the appropriate source of S will depend on the soil properties such as leaching potential, pH and organic matter content. The need for additional nutrients present in the S fertilizer is also a consideration. The requirement for an immediately soluble source of S will also influence the selection of a specific fertilizer source. [BG](#)

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