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Sulphur-Oxidizing Bacteria: A Sustainable Microbial Tool for Enhancing Soil Fertility and Crop Productivity

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ABSTRACT

Sulphur-oxidizing bacteria (SOB) are key microbial agents that transform reduced or elemental sulphur into plant-available sulphate, thereby ameliorating sulphur deficiency in soils, a growing concern across agro-ecosystems globally. Through biochemical oxidation processes, SOB contribute to sulphur nutrition, enhance nutrient availability (e.g., zinc, iron), and may support plant growth promotion via auxiliary mechanisms such as phosphate solubilization and phytohormone production. Empirical studies in soybean, onion, mungbean and other crops demonstrate significant improvements in yield, nutrient content, and stress resilience with SOB inoculation. However, the efficacy of SOB depends critically on soil physico-chemical properties, microbial community context, and formulation stability. This article reviews current understanding of SOB's agricultural role, highlights recent findings, discusses challenges, and outlines future directions for research and application.

INTRODUCTION

Sulphur (S) is an essential macronutrient for plants, vital for the synthesis of sulphur-containing amino acids (e.g., cysteine, methionine), proteins, vitamins, and various metabolic and defence compounds. In recent decades, sulphur deficiency has become increasingly common in agro-ecosystems worldwide, owing to factors such as intensive cropping, high biomass removal, widespread use of non-S fertilizers (N, P, K), reduced atmospheric sulphur deposition, and insufficient S recycling. Consequently, sulphur deficiency can lead to stunted growth, reduced yield, and lower crop quality, particularly in S-demanding oilseed, pulse and vegetable crops (Patel *et al.,* 2023).

One sustainable solution to counter this deficiency is the use of sulphur in the reduced or elemental form (S^0). However, plants cannot directly absorb S^0; it must first be oxidized to sulphate (SO_4^{2-}), the bioavailable form. This oxidation is largely mediated by specialized soil microbes collectively referred to as sulphur-oxidizing bacteria (SOB). The harnessing of SOB as bioinoculants or biofertilizers offers a promising, eco-friendly strategy to improve soil S-status, plant nutrition, and crop yield without reliance solely on chemical fertilizers (Patel *et al.,* 2023).

Role of Sulphur-Oxidizing Bacteria in Agriculture

Biochemical Basis and Diversity

Sulphur-oxidizing bacteria are chemolithotrophic or mixotrophic microbes that derive energy by oxidizing reduced sulphur compounds (e.g., elemental sulphur S^0, sulphide, thiosulfate, sulphite) into sulphate under aerobic conditions. This process involves key enzymes such as flavocytochrome c-sulphide dehydrogenase, sulphite oxidase, and other components of the sulphur oxidation pathway. Among the commonly studied genera are those formerly grouped under Thiobacillus, along with other *Bacillus* and *Pantoea* species identified in recent isolates(Ranadey *et al.,* 2023).

SOB-mediated oxidation of applied elemental sulphur typically converts about **40–51%** of S^0 to plant-available sulphate under favourable soil conditions.

Enhancement of Sulphur Nutrition and Crop Yield

By converting S^0 or other reduced sulphur into sulphate, SOB ensure a steady supply of sulphur to crops, especially in sulphur-deficient soils. Several studies have demonstrated tangible benefits in yield, quality, and nutrient composition across crops:

- A recent field trial on summer soybean in Gujarat (India) reported that application of a sulphur source along with SOB (at 3 L/ha) significantly increased seed and stover yield, and improved oil and protein content compared with control treatments.
- In onion (Allium cepa L.) pot experiments, inoculation with SOB strains (e.g., *Bacillus spizizenii*, *Priestia aryabhattai*) combined with sulphur fertilization enhanced plant height, bulb weight, nutrient uptake (N, P, K, S), photosynthetic pigments, and biochemical constituents such as amino acids and carbohydrates.
- In mungbean (Vigna radiata), seed-priming with SOB isolated from rhizosphere soils improved seedling vigour index under in-vitro conditions, indicating potential for early-stage growth promotion (Khallaf *et al.,* 2025).

Beyond basic S nutrition, SOB inoculation has been associated with improved mobilization of other nutrients (e.g., zinc, iron), especially in micronutrient-deficient soils. For instance, co-application of SOB with micronutrient sprays enhanced Fe and Zn uptake in groundnut and wheat (Jadhav *et al.,* 2025).

Role in Soil Health, Stress Mitigation and Biocontrol

SOB activity can contribute to soil acidification (*via* production of sulfuric acid), which helps in solubilizing otherwise unavailable nutrients in alkaline or calcareous soils, improving overall nutrient availability.

Moreover, SOB have shown promise in biocontrol: sulphur oxidation can suppress soil-borne pathogens by modulating soil pH and enhancing formation of sulphur-containing defence metabolites (e.g., isothiocyanates, glucosinolates) in plants, which act as natural repellents or antimicrobials (Nandni *et al.,* 2023).

Additionally, SOB-based inoculation has improved plant tolerance against abiotic stresses such as salinity and drought. In a study with a halophytic plant, SOB improved salt/drought stress resilience — suggesting a broader role in enhancing stress tolerance under marginal conditions (Nandni *et al.,* 2023).

Challenges and Limitations

Despite the many promising aspects, the deployment of SOB in mainstream agriculture faces several challenges:

- **Soil and environmental dependency:** The efficiency of S^0 oxidation by SOB is strongly influenced by soil pH, temperature, moisture, oxygen availability, and the existing microbial community. In calcareous or poorly aerated soils, oxidation rates may be significantly reduced.
- **Variability of microbial survival & persistence:** While inoculation may initially boost SOB population and activity, long-term survival, colonization, and functionality under field conditions remain uncertain, especially under repeated cropping cycles (Ranadey *et al.,* 2023)
- **Formulation and delivery constraints:** Development of stable, effective, and easy-to-apply biofertilizer formulations (e.g., powder, granule, liquid) is still a limiting factor.
- **Soil microbiome disruption risk:** Some recent studies show that sulphur application (especially in high doses) can shift soil microbial community structure, sometimes suppressing beneficial microbial processes, affecting overall soil health.
- **Incomplete understanding of biochemical pathways:** Though many SOB pathways are known, the full range of metabolic interactions (e.g., with plant roots, other microbes, nutrient cycles) in diverse soil-plant systems needs deeper study (Bhattacharya *et al.,* 2022).

Future Perspectives

Given the potential and limitations, the future of SOB in agriculture may evolve along several research and application pathways:

- **Biofertilizer development and field trials:** More field-level trials (across diverse agro-climatic zones, soil types, crop species) are needed to evaluate SOB-based biofertilizers under real-world farming conditions.
- **Formulation improvements:** Research on robust, stable inoculum formulations (e.g., peat-based, granular, encapsulated) to ensure survival, viability and easy application by farmers.
- **Integrated nutrient management (INM):** Combining SOB inoculation with reduced doses of chemical fertilizers or organic manures to optimize fertilizer use efficiency, reduce environmental load, and lower cost (Nadeem *et al.,* 2023).
- **Soil microbiome engineering:** Studying interactions between SOB and native microbial communities, to design microbial consortia that synergistically enhance

nutrient cycling, soil health, and plant resilience.

- **Stress-resilience & biocontrol applications:** Exploiting SOB not only for sulphur nutrition but also for enhancing plant tolerance to abiotic (salinity, drought) and biotic (pathogen) stresses; possibly combining with other beneficial microbes (e.g., PGPR, mycorrhizae) (Chaudhary *et al.,* 2023).
- **Molecular and metabolic research:** Deepening understanding of SOB metabolic pathways, genetic regulation, and ecological adaptation to different soils, to engineer or select more efficient and versatile strains.

CONCLUSION

sulphur-oxidizing bacteria (SOB) represent a promising, eco-friendly tool in sustainable agriculture, capable of transforming inert sulphur into plant-available sulphate, improving nutrient availability, enhancing crop yield and quality, and possibly contributing to stress resilience and biocontrol. Recent empirical studies in soybean, onion, mungbean and other crops demonstrate clear agronomic benefits. However, realizing their full potential requires surmounting challenges related to soil dependency, microbial survival, formulation, and ecological balance. Future research and development efforts focusing on field validation, biofertilizer formulation, integrated nutrient management, and microbiome optimization are critical. For sulphur-deficient soils, like many in India and other parts of the world, SOB-based solutions could significantly contribute to improving soil health, crop productivity, and sustainable farming.

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