



## The Hidden Sulphur War: How Plants and Pathogens Battle for Survival

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In the silent world of plants and microbes, a fierce biochemical battle is constantly being fought beneath our feet and within plant tissues. While we often hear about nitrogen, phosphorus, and potassium as the most important nutrients for crops, sulphur has recently emerged as a powerful but overlooked player in plant health and disease resistance. Scientists now describe this interaction as a “sulphur war”, where plants and invading pathogens compete intensely for this essential element to determine the outcome of infection. This invisible war not only influences crop productivity but also offers exciting new opportunities for sustainable disease management and plant breeding (Wang *et al.*, 2022)..

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### Why Sulphur Matters More Than We Thought

Sulphur is not just another mineral nutrient. It is a building block of essential amino acids such as cysteine and methionine, antioxidants like glutathione, and powerful antimicrobial compounds including phytoalexins and defensins. These sulphur-containing molecules form the backbone of plant immune responses. Historically, sulphur was widely used as a fungicide as early as the 19th century. Interestingly, when industrial sulphur emissions were reduced in Europe during the 1980s for environmental protection, farmers observed an unexpected increase in crop diseases. This surprising outcome revealed a strong link between sulphur nutrition and plant immunity, leading to the concept of “sulphur-induced resistance” (Bloem *et al.*, 2015).

### How Pathogens Steal Sulphur from Plants

Plant pathogens-including bacteria, fungi, and oomycetes- require sulphur for their growth, reproduction, and virulence. Many microbes have evolved sophisticated systems to extract sulphur from their plant hosts.

**Bacterial Strategies:** Plant-pathogenic bacteria such as *Xanthomonas* possess specialized transporters that import sulphate and organic sulphur compounds. Research has shown that disrupting these sulphur transport systems weakens bacterial virulence, reducing their ability to form biofilms and infect plants (Kertesz, 2000).

**Fungal Tactics:** Fungal pathogens rely heavily on sulphur metabolism. Studies in rice blast fungus (*Magnaporthe oryzae*) revealed that mutations in sulphur assimilation genes

drastically reduce spore production and disease severity. Remarkably, these defects could be reversed by supplying sulphur-containing amino acids, confirming sulphur's central role in fungal pathogenicity plant (Solomon *et al.*, 2000).

**Oomycete Adaptations:** Oomycetes such as *Phytophthora* species, responsible for devastating crop diseases like late blight, show unusually high numbers of sulphate transporter genes. This suggests that sulphur uptake is tightly regulated during infection. Some species even shift their sulphur acquisition strategies depending on whether they are in biotrophic (living tissue) or necrotrophic (dead tissue) stages.

**Plants Fight Back: Sulphur as a Weapon:** Plants do not passively surrender their sulphur reserves. Instead, they actively manipulate sulphur transport and metabolism to starve pathogens while strengthening their own defenses.

**Sulphur Transport: The Frontline Defense:** Plant roots absorb sulphate from soil using specialized transporter proteins called SULTRs. During infection, plants can alter the activity of these transporters to restrict sulphur availability at infection sites, making it harder for pathogens to thrive. Some pathogens attempt to counter this strategy by releasing effector proteins that hijack plant sulphur transport systems. For example, rice pathogens can activate specific sulphate transporters in host cells to increase sulphur availability for bacterial growth.

### Sulphur-Containing Molecules: The Plant's Arsenal

**Cysteine – The First Line of Defense:** Cysteine is the first sulphur-containing compound produced during sulphate assimilation. Beyond its role in protein synthesis, cysteine directly inhibits fungal growth. Experiments have shown that spraying cysteine on grapevine leaves reduced trunk disease severity by suppressing fungal pathogens.

**Glutathione – The Master Regulator:** Glutathione acts as both an antioxidant and a signaling molecule. During pathogen attack, changes in glutathione redox balance trigger defense gene activation and control reactive oxygen species. This dual role allows plants to both neutralize cellular damage and activate immune responses.

**Sulphur-Rich Antimicrobial Peptides:** Plants also produce sulphur-rich antimicrobial peptides such as defensins and thionins. These molecules can puncture fungal membranes, disrupt pathogen metabolism, and trigger programmed cell death in invading microbes.

**Phytoalexins and Glucosinolates:** *Brassicaceae* crops like cabbage, mustard, and broccoli synthesize sulphur-containing compounds such as camalexin and glucosinolates. These chemicals act as natural antibiotics, deterring bacteria, fungi, and insects.

### The Tug of War: Nutrient Competition During Infection

During infection, plants initiate a nutrient restriction strategy, limiting access to sugars, iron, and sulphur. This nutrient starvation weakens pathogen growth. In response, pathogens activate alternative uptake systems or manipulate host transporters to regain access. Transcriptome studies revealed that bacterial pathogens dramatically increase sulphur transporter gene expression when exposed to plant immune responses. This indicates that sulphur starvation is a real stress experienced by invading microbes

**Sulphur and Plant Hormones: A Complex Cross-Talk:** Sulphur availability also influences plant hormone signaling pathways that regulate immunity.

**Sulphur Deficiency Activates Salicylic Acid Defense:** When plants experience sulphur deficiency, they activate the salicylic acid (SA) pathway, which enhances resistance against biotrophic pathogens such as *Pseudomonas syringae*. This response is mediated by the key regulator protein NPR1 (Han *et al.*, 2013).

**Sulphur Excess Strengthens Defense Against Necrotrophs:** Interestingly, excess sulphur shifts plant immunity toward jasmonic acid (JA)-mediated defenses, improving resistance against necrotrophic fungi like *Botrytis cinerea*. However, this comes at the cost of increased vulnerability to biotrophic pathogens. This delicate balance highlights sulphur as a master regulator of immune pathway cross-talk.

## Case Studies: Sulphur in Action

**Rice Blast Disease:** Deletion of sulphur assimilation genes in rice blast fungus drastically reduced spore formation and virulence. Supplying methionine restored pathogenicity, proving that sulphur metabolism is essential for disease development (Li *et al.*, 2020).

**Arabidopsis Immune Response:** Sulphur-deprived Arabidopsis plants showed increased resistance to bacterial pathogens but became more susceptible to fungal necrotrophs. Conversely, sulphur-rich diets enhanced fungal resistance while weakening bacterial defense. This demonstrates how sulphur nutrition shapes disease outcomes (Criollo-Arteaga *et al.*, 2021).

## Future Opportunities: Using Sulphur for Sustainable Disease Control

Understanding the sulphur war opens new doors for crop protection include breeding crops with optimized sulphur transporter regulation, targeting pathogen sulphur metabolism as a disease control strategy, precision sulphur fertilization to enhance plant immunity and reducing dependence on chemical pesticides. With increasing demand for sustainable agriculture, sulphur-based strategies could become powerful tools for eco-friendly disease management.

## Conclusion: The Silent Warrior in Plant Immunity

Sulphur is no longer just a secondary nutrient. It is a central player in the battlefield between plants and pathogens. From strengthening immune signaling to starving invading microbes, sulphur orchestrates multiple layers of plant defense. As researchers continue to unravel this biochemical warfare, sulphur may become the next frontier in sustainable crop protection helping farmers grow healthier crops while protecting our environment.

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