

Vanadium in Plant Systems: A Double-Edged Sword Between Growth Promotion and Phytotoxicity

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Vanadium is an emerging trace element in plant science, exhibiting dual behavior as both a growth-promoting agent and a phytotoxic contaminant. At low concentrations, vanadium enhances seed germination, biomass production, and nutrient metabolism, while at higher levels it disrupts photosynthesis, nutrient uptake, and induces oxidative stress. Its impact on plants is strongly governed by speciation, soil properties, and bioavailability. Although plants possess detoxification mechanisms such as sequestration and antioxidant defense, increasing environmental accumulation poses risks to agriculture and food safety. Understanding vanadium's context-dependent role is essential to resolve its classification and develop sustainable management and remediation strategies in agroecosystems.

Vanadium

Trace elements play a complex role in plant systems, often acting as essential nutrients at low concentrations while becoming toxic at higher levels. Among these elements, vanadium has gained increasing attention due to its dualistic behavior and rising environmental presence. Traditionally regarded as a non-essential element for higher plants, vanadium is now recognized for its potential to influence plant growth and metabolism under specific conditions (Altaf et al., 2022). At low concentrations, it may stimulate physiological processes, whereas at elevated levels, it exerts pronounced toxic effects on plant development.

The increasing industrial use of vanadium in steel production, fossil fuel combustion, and chemical industries has led to its widespread release into the environment. Consequently, vanadium accumulation in soils has become a growing concern, particularly in agricultural systems located near industrial zones (Wnuk, 2023). This raises critical questions regarding its role in plant biology: Is vanadium a beneficial element that enhances plant performance, or does it primarily act as a phytotoxic pollutant?

This spotlight aims to critically examine the dual nature of vanadium in plants by exploring its behavior in the soil–plant system, its beneficial and toxic effects, and the factors governing its impact. Understanding this balance is essential for assessing ecological risks and determining whether vanadium should be considered a beneficial micronutrient or an emerging environmental hazard.

Occurrence and Behavior in the Soil–Plant System

Vanadium is a widely distributed transition metal found in soils, water bodies, and the atmosphere. It originates from both natural processes, such as weathering of parent rocks, and anthropogenic activities, including mining, smelting, fossil fuel combustion, and industrial emissions (Yang et al., 2022). Its environmental abundance has increased significantly due to rapid industrialization, particularly in regions with intensive metallurgical activities.

In soils, vanadium exists in multiple oxidation states, with V(IV) and V(V) being the most stable under environmental conditions. These oxidation states strongly influence its mobility, bioavailability, and toxicity. Vanadium speciation is highly dependent on soil properties such as pH, redox potential, organic matter content, and microbial activity. Under aerobic conditions,

vanadium typically exists as vanadate (V^{5+}), an oxyanion structurally like phosphate (Hanus-Fajerska et al., 2021).

Plant uptake of vanadium primarily occurs through roots, where it is absorbed from the soil solution. Due to its similarity to phosphate, vanadate can enter plant cells via phosphate transport systems. However, once inside the plant, vanadium is largely retained in the roots, with limited translocation to aerial tissues (Imtiaz et al., 2015). This restricted movement is thought to be a protective mechanism that minimizes damage to photosynthetically active organs. The extent of vanadium uptake and translocation varies among plant species and is influenced by both environmental and physiological factors. Soil bioavailable vanadium, rather than total concentration, plays a decisive role in determining plant accumulation (Haak and Indraratne, 2023). Thus, understanding vanadium behavior in the soil–plant continuum is fundamental to evaluating its biological effects.

Beneficial Effects of Vanadium

Although vanadium is not classified as an essential element for higher plants, numerous studies have demonstrated its beneficial effects at low concentrations. These positive effects are often observed as stimulation of plant growth and enhancement of physiological processes.

Low levels of vanadium have been reported to promote seed germination, root elongation, and overall biomass production. It can enhance chlorophyll synthesis, leading to improved photosynthetic efficiency. Additionally, vanadium has been shown to influence nutrient metabolism, particularly nitrogen assimilation, suggesting a role in improving plant nutritional status (Zwolak, 2020). One of the notable functions attributed to vanadium is its involvement in nitrogen fixation processes, particularly in certain microorganisms and symbiotic systems. While this role is more pronounced in lower organisms, it suggests that vanadium may indirectly contribute to plant growth by supporting nitrogen metabolism (Chen et al., 2021).

The beneficial effects of vanadium are highly concentration-dependent and often follow a hormetic response, where low doses stimulate growth while higher doses inhibit it. This has led to the classification of vanadium as a “quasi-beneficial” element, one that is not essential but can enhance plant performance under specific conditions (Roychoudhury, 2020).

Toxic Effects and Mechanisms

At elevated concentrations, vanadium becomes highly toxic to plants, affecting both physiological and biochemical processes. The toxic effects of vanadium are well-documented and include inhibition of seed germination, suppression of root and shoot growth, and reduction in overall plant biomass (Chen et al., 2021). One of the primary targets of vanadium toxicity is photosynthesis. High levels of vanadium disrupt chlorophyll synthesis and damage the photosynthetic apparatus, leading to reduced carbon assimilation (Altaf et al., 2020). Additionally, vanadium interferes with nutrient uptake by competing with essential elements such as phosphorus, thereby causing nutrient imbalances. A key mechanism of vanadium toxicity is its structural similarity to phosphate. Vanadate can substitute for phosphate in biochemical reactions, disrupting ATP synthesis and enzyme activity.

Vanadium Distribution in Soil Plant System

A dual-role element: Beneficial at low levels, toxic at high levels

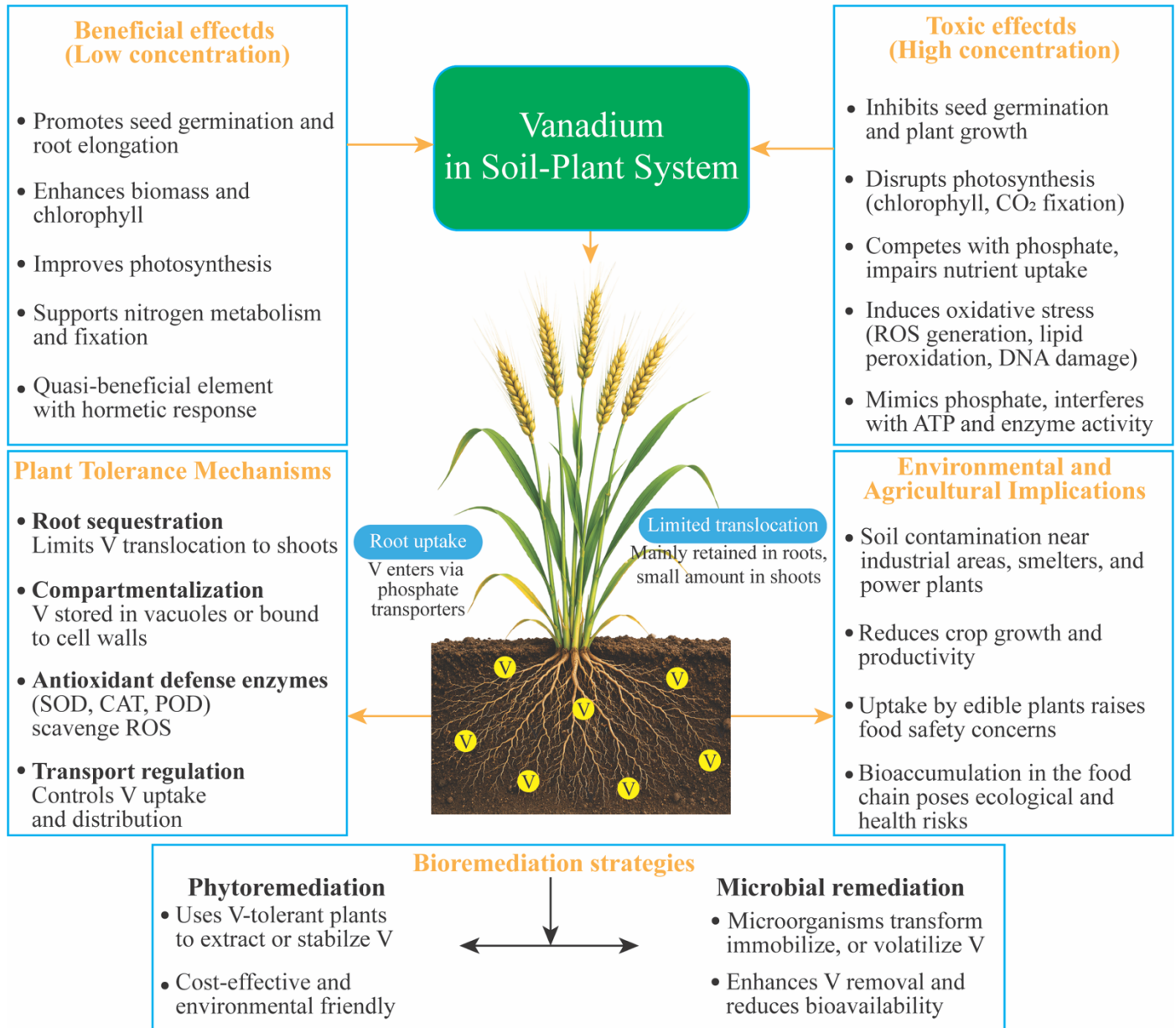


Fig. 1. Vanadium dynamics in the soil–plant system: from uptake to ecological impact.

This interference with phosphate metabolism has far-reaching consequences for cellular energy production and metabolic regulation. Vanadium toxicity is also associated with the generation of reactive oxygen species, which cause oxidative stress within plant cells. Excessive ROS production leads to lipid peroxidation, protein damage, and DNA degradation. These oxidative damages impair cellular integrity and ultimately result in reduced plant growth and vitality.

Plant Tolerance Mechanisms

Plants have evolved several strategies to cope with vanadium stress and mitigate its toxic effects. One of the primary defense mechanisms is the sequestration of vanadium in the root system, which limits its translocation to shoots and protects vital tissues (Li et al., 2024). Within plant cells, vanadium

can be compartmentalized into vacuoles or bound to cell wall components, reducing its interaction with sensitive cellular processes. This compartmentalization is a key detoxification strategy that minimizes damage to metabolic pathways (Smoleń et al., 2021). Plants also activate antioxidant defense systems in response to vanadium-induced oxidative stress. Enzymes such as superoxide dismutase, catalase, and peroxidases play a crucial role in scavenging reactive oxygen species and maintaining cellular redox balance (Kumar et al., 2022). Additionally, plants may regulate the expression of transport proteins to control vanadium uptake and distribution. By limiting the entry of vanadium into cells, plants can reduce its toxic effects. These tolerance mechanisms vary among species and contribute to differences in sensitivity to vanadium (Shireen et al., 2021). Understanding these adaptive responses is important for identifying plants suitable for phytoremediation and for improving crop resilience in contaminated environments.

Environmental and Agricultural Implications

The increasing presence of vanadium in the environment poses significant challenges for agriculture and ecosystem health. Industrial activities have led to elevated vanadium concentrations in soils, particularly near mining areas, smelters, and power plants. High levels of vanadium in agricultural soils can adversely affect crop growth and productivity (Imtiaz et al., 2015). Moreover, the accumulation of vanadium in edible plant parts raises concerns about food safety and potential health risks to humans and animals. Vanadium can enter the food chain through plant uptake, leading to its bioaccumulation in higher trophic levels (Wnuk, 2023). This highlights the need for monitoring and managing vanadium contamination in agricultural systems. From an environmental perspective, vanadium pollution can disrupt soil microbial communities and ecological processes. Its impact on soil fertility and biodiversity further underscores the importance of understanding its behavior and effects. Addressing these challenges requires developing effective strategies for monitoring, risk assessment, and remediation of vanadium-contaminated soils.

Future Perspectives

Despite considerable progress, key knowledge gaps remain regarding vanadium behavior in plant systems. A major challenge is determining whether vanadium functions as a beneficial element or primarily induces stress-related adaptive responses. Further research is needed to clarify the molecular mechanisms governing its uptake, transport, and detoxification, particularly using advanced genomics and metabolomics approaches. Establishing clear toxicity thresholds across different crops and soil conditions is essential for accurate risk assessment. Moreover, field-based studies are necessary to validate laboratory findings. The development of phytoremediation strategies using vanadium-tolerant plants, along with a better understanding of plant-microbe interactions, offers promising solutions. Overall, vanadium's role is highly context-dependent, requiring integrated research to ensure sustainable agricultural and environmental management.

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The author contributed to all aspects of the manuscript.

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