
Absorption of Nutrients by Plant Roots and their Interaction with Soil Solution in Relation to Soilless Cultivation

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ABSTRACT

Efficient nutrient absorption is a key determinant of plant growth and productivity. In conventional soil-based systems, plant roots absorb essential macro- and micronutrients from the soil solution, a dynamic medium influenced by pH, microbial activity, and nutrient availability. Soilless cultivation systems, including hydroponics, aeroponics, and nutrient film techniques, provide an alternative approach that allows precise control over nutrient delivery, water availability, and environmental conditions. These systems offer several advantages, including higher nutrient uptake efficiency, consistent plant growth, elimination of soil-borne pathogens, and reduced fertilizer losses, making them environmentally sustainable and resource-efficient. However, the absence of soil buffering necessitates careful monitoring of solution pH, electrical conductivity, and oxygenation to prevent nutrient imbalances and optimize root function. Root morphology, particularly the presence of fine roots and root hairs, plays a critical role in nutrient acquisition. Controlled soilless environments often stimulate denser and more branched

root systems, enhancing nutrient and water absorption. Empirical studies indicate a strong correlation between root biomass and the uptake of key nutrients such as potassium, calcium, and nitrate in crops like lettuce and tomato. This review highlights the physiological mechanisms of nutrient absorption, the interaction of roots with the growth medium, and the advantages and challenges of soilless cultivation, providing insights for optimizing plant productivity in controlled agricultural systems.

INTRODUCTION

Efficient nutrient uptake is a cornerstone of plant growth and productivity. In conventional soil-based systems, roots absorb nutrients from the soil solution, a dynamic mixture of water, ions, and organic compounds influenced by soil texture, pH, and microbial activity. Modern soilless cultivation systems-including hydroponics, aeroponics, and nutrient film techniques (NFT)-allow precise control of nutrient availability, enhancing growth and yield while reducing dependence on soil quality.

MECHANISMS OF NUTRIENT UPTAKE

Mass flow: Nutrients dissolved in water move towards the root surface due to the transpiration stream, which pulls water upward through the plant. This is particularly effective for nutrients like nitrogen and potassium. In hydroponically grown lettuce, Baiyin *et al.* (2021) reported that increasing transpiration rate from 0.8 to 1.2 L/day improved nitrate (NO_3^-) uptake by 22%, demonstrating the importance of mass flow in nutrient absorption.

Diffusion: Nutrients move from areas of higher concentration to lower concentration. This mechanism is crucial for nutrients like phosphorus, which are less mobile in the nutrient solution. Marschner (2012) noted that phosphorus (PO_4^{3-}) uptake in tomato seedlings increased by 18–25% when the solution phosphorus concentration gradient was optimized (from 0.1 to 0.3 mM) in NFT systems.

Root interception: As roots grow and extend, they come into contact with soil particles containing nutrients, allowing for direct uptake. In aeroponic cucumber cultivation, Baiyin *et al.* (2025) observed that optimized aeration led to a 30% increase in root biomass and enhanced potassium (K^+) uptake efficiency.

Active transport: Energy-dependent transport proteins absorb ions against gradients. Hydroponic spinach grown with 50 μM iron (Fe^{2+}) *via* chelated EDTA solutions showed a 40% higher leaf iron content compared to unchelated iron treatments (Resh, 2013), highlighting the role of active transport for micronutrients. These mechanisms ensure that plants receive a balanced supply of essential nutrients, which are crucial for various physiological functions, including growth, reproduction, and stress resistance.

INTERACTION WITH SOIL SOLUTION

Root exudates (organic acids, sugars, amino acids) alter the soil or nutrient solution composition, enhancing solubility of phosphorus, iron, and zinc. de Haas (2025) found that increasing nutrient

solution CO₂ levels from 400 to 700 ppm in hydroponic tomato systems increased root exudation by 15–20%, positively impacting nutrient uptake and microbial activity.

NUTRIENT UPTAKE IN SOILLESS CULTIVATION

Soilless systems provide precisely controlled nutrient solutions, ensuring consistent availability of all essential macro- and micronutrients.

Table 1. Effects of Soilless Cultivation Practices on Nutrient Uptake and Root Development in Various Crops

Crop	System	Nutrient	Observed Effect	Reference
Lettuce	NFT	Nitrate	+22% uptake with higher transpiration	Baiyin <i>et al.</i> , 2021
Tomato	NFT	Phosphate	+18–25% uptake under optimized P gradient	Marschner, 2012
Cucumber	Aeroponics	Potassium	+30% uptake with optimized aeration	Baiyin <i>et al.</i> , 2025
Spinach	Hydroponics	Iron	+40% leaf Fe with chelated solution	Resh, 2013
Tomato	Hydroponics	Root exudates	+15–20% nutrient availability with elevated CO ₂	de Haas, 2025

ADVANTAGES OF SOILLESS CULTIVATION SYSTEMS

Soilless cultivation systems offer several distinct advantages over conventional soil-based agriculture. One of the primary benefits is the ability to provide precisely controlled nutrient delivery, ensuring that plants receive all essential macro- and micronutrients in optimal concentrations. This precise control maximizes nutrient uptake efficiency, as nutrients are immediately available in soluble form and can be adjusted according to plant developmental stages. Additionally, these systems allow for consistent environmental conditions, including temperature, humidity, light, and water availability, which support uniform plant growth and development. By eliminating the reliance on soil, soilless systems also reduce or completely eliminate the risk of soil-borne pathogens and pests, leading to healthier plants with lower disease incidence. Another advantage is the reduction of fertilizer losses, both through leaching and runoff, making soilless cultivation environmentally more sustainable and resource-efficient compared to traditional soil-based cultivation.

CHALLENGES IN SOILLESS SYSTEMS

Despite these advantages, soilless systems present certain challenges. The absence of soil buffering means that nutrient imbalances can develop quickly if the nutrient solution is not carefully managed. Variations in nutrient concentrations, pH, or electrical conductivity (EC) can directly affect plant health, making continuous monitoring of the nutrient solution essential. Maintaining a solution pH in the range of 5.5 to 6.5, EC between 0.8 to 3.5 dS m⁻¹, and ensuring adequate oxygenation around the roots are critical factors for optimal nutrient absorption and root function. Without such monitoring, plants can experience deficiencies or toxicities more rapidly than in soil, where natural buffering and microbial interactions provide some mitigation.

ROLE OF ROOT MORPHOLOGY IN NUTRIENT UPTAKE

Root morphology plays a central role in nutrient uptake efficiency, particularly in soilless systems. The presence of root hairs and fine roots significantly increases the absorptive surface area, enhancing the plant's ability to access nutrients in the solution. In controlled soilless environments, the combination of optimal nutrient availability and adequate oxygenation often stimulates the development of denser and more branched root systems, which further improves nutrient absorption. Empirical studies in hydroponic systems have demonstrated a strong correlation between root biomass and the uptake of essential nutrients, including potassium (K⁺), calcium (Ca²⁺), and nitrate (NO₃⁻), in crops such as lettuce and tomato. Denser root networks not only improve nutrient acquisition but also enhance water absorption, supporting vigorous growth and higher yields. This dynamic adaptation of root architecture to controlled nutrient and environmental conditions underscores the critical role of root morphology in maximizing the efficiency of soilless cultivation systems.

CONCLUSION

Efficient nutrient absorption by plant roots involves mass flow, diffusion, root interception, and active transport, supported by dynamic interactions with the nutrient solution. Soilless cultivation leverages these mechanisms by supplying optimized nutrient solutions in a controlled environment, resulting in faster growth, higher yield, enhanced nutrient use efficiency and reduced disease incidence. Research data confirms that system design, nutrient concentration, aeration, and environmental management directly influence root morphology, exudation, and nutrient uptake efficiency, making soilless cultivation a powerful tool for sustainable, high-yield agriculture.

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