Transpiration and water movement through plants

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***Abstract*—Water movement through plants is fundamental to leaf function, mineral distribution, and sustained growth, yet it is often described too narrowly as either root uptake or leaf water loss. This paper synthesises accepted evidence on how water moves from a hydroponic root zone into roots, through vascular tissues, and ultimately to the atmosphere through stomata. The review clarifies that whole-plant water transport depends on a continuous pathway that links radial movement into the stele with long-distance xylem flow and transpiration-driven demand at evaporative surfaces. It also explains why stomata matter: they regulate the trade-off between carbon dioxide entry and water loss, thereby shaping the negative pressure gradients that sustain water ascent. A second focus is the relationship between transpiration, water transport, and mineral movement. The evidence shows that transpiration contributes to mass flow and solute transport, but mineral uptake cannot be reduced to transpiration alone because root barriers, transport pathways, ion availability, oxygen status, and solution management also constrain movement. For hydroponic interpretation, the central implication is that transpiration should be understood as a driver of integrated plant water relations rather than as a solitary determinant of nutrient acquisition. This synthesis provides a scientifically bounded explanation of why transpiration matters in soilless plant systems.**

I. Introduction

Water movement through plants is best understood as a continuous process that begins where water becomes available to the root surface and extends to evaporative loss from leaves. Evidence on nutrient acquisition shows that roots interact with their surrounding medium through interception, mass flow, and diffusion, and these processes help explain how water and dissolved ions are brought into contact with absorbing tissues. In that sense, root uptake is not an isolated event but the first stage of a longer transport pathway that supports hydration, leaf function, and internal solute distribution. However, evidence focused on root zone processes alone does not fully explain how water is pulled through the shoot, so a whole-plant account is required to answer how water moves from roots to leaves in hydroponic systems [1], [2].

A second issue is that discussions of water movement often separate root supply from stomatal water loss, even though the plant functions through their coupling. The available evidence identifies physical properties around roots and rhizosphere processes as important influences on water availability and nutrient movement, but this line of work does not itself explain stomatal regulation of transpiration and gas exchange. That gap matters because the reader-facing question is not only how roots acquire water, but why transpiration matters once water has entered the plant. This paper therefore focuses on the continuous root-to-shoot pathway, the role of vascular tissues, and the importance of stomata, while remaining within an explanatory physiological scope rather than turning the discussion into environmental control advice [1], [3].

II. Background and Scope

Relevant background from recent plant physiology work shows that nutrient availability can alter photosynthetic capacity and the carbon costs of nitrogen acquisition without necessarily changing the integrated leaf-to-air CO2 ratio under non-limiting water conditions. This is important because it demonstrates that plant performance responds to nutrient status through more than one pathway, and that water relations cannot be interpreted in isolation from broader physiological demand. At the same time, such studies do not directly establish the accepted physical mechanism of root-to-shoot water transport. Their value for the present topic is therefore conceptual rather than definitive: they help frame transpiration within integrated plant function, while leaving the explanation of long-distance water ascent to other evidence [4], [5].

The same background also helps define the scope of stomatal function. Because ci/ca acts as an integrated indicator of stomatal conductance and photosynthetic activity, unchanged ci/ca alongside increased carboxylation capacity implies coordinated adjustment rather than a simple one-way response. This supports a central principle for the present paper: stomata regulate both carbon dioxide exchange and water loss, so transpiration matters not only because water exits the leaf, but because stomatal behaviour couples leaf gas exchange to hydraulic demand. The present synthesis uses that principle to explain how water movement through plants is linked to leaf function, while avoiding unsupported claims that would treat stomata as the only control point in plant water relations [4].

This scope also helps answer the mineral transport question carefully. If nutrient availability changes acquisition costs and photosynthetic capacity without directly tracking a single transpiration signal, then mineral uptake cannot be described as a purely passive consequence of water flow. Instead, transpiration should be treated as one important contributor to mass movement and xylem delivery, while root transport pathways, local ion conditions, and plant regulatory processes remain essential. Accordingly, this paper does not present transpiration as an all-purpose explanation for nutrient uptake. It instead develops a more bounded argument: water movement through plants is strongly shaped by transpiration-driven gradients, but the transport of minerals depends on both hydraulic flow and biologically controlled uptake processes [4].

III. Core Concepts and Mechanisms

The accepted explanation of root-to-shoot water transport centres on xylem flow under the cohesion-tension framework. In this account, water moves through continuous columns in xylem because evaporation from leaf surfaces generates negative pressure gradients that pull water upward through the vascular system. This mechanism links root uptake to leaf demand, and it remains the clearest basis for explaining why transpiration can drive whole-plant water movement. Evidence on xylem physiology also indicates that this transport pathway is not merely a rigid pipe, because cavitation, pit properties, and hydraulic conductance influence the reliability and limits of flow. Alternative discussions of root pressure and embolism refilling are informative, but they do not replace the mainstream explanation of transpiration-driven ascent in the present evidence base [6], [7].

Before water enters the long-distance xylem stream, it must move radially through root tissues. Evidence on root transport describes apoplastic, symplastic, and trans-cellular routes that carry water and solutes from the root surface towards the stele, while endodermal barriers and transporter polarity influence which substances reach the vascular cylinder. This radial stage matters because the hydroponic root zone does not deliver water directly to the leaf; it first feeds a selectively structured root system whose tissues regulate entry into the transport stream. The implication is that the vascular pathway begins with biological filtering as well as physical movement, so any explanation of water ascent must account for both the root interface and the xylem continuum above it [8].

Stomata provide the most direct connection between leaf gas exchange and whole-plant water loss. Evidence from controlled-environment studies shows that blue light strongly influences stomatal opening, with photoreceptor signalling increasing conductance and thereby elevating transpiration, while other signals such as ABA can override opening responses and promote closure under water stress. These findings explain why stomata matter to water movement through plants: by regulating the aperture through which water vapour exits, they help determine the evaporative demand that sustains negative pressure in xylem and thus root-to-shoot flow. The limitation is equally important, because evidence on light-regulated stomata clarifies water loss and gas exchange well, but it does not by itself explain mineral movement in a complete way [9], [10].

IV. Evidence Synthesis

When the evidence is read together, transpiration emerges as a driver of continuity rather than a solitary controller of plant function. Xylem physiology supports the view that evaporative demand at the leaf generates the tension needed for upward movement in continuous water columns, while root transport studies show that entry into that stream depends on structured radial pathways and tissue barriers. Work on nutrient movement to roots adds a further layer by showing that mass flow, diffusion, and interception all contribute to bringing dissolved substances into the uptake zone. The most defensible synthesis is therefore that transpiration helps maintain bulk flow from the root zone into and through the plant, but its effect operates within a larger transport architecture that begins at the root surface and continues through selective tissues and vascular conduits [1], [7], [8].

Stomata are central to this integrated picture because they regulate the point at which internal water is lost to the atmosphere while simultaneously supporting carbon dioxide entry for photosynthesis. Evidence on blue-light responses shows that stomatal opening is an active physiological process involving H+-ATPase phosphorylation and K+ influx under non-stress conditions, whereas drought-associated hormonal signalling can reverse that state and limit transpiration. This matters for the present topic because it gives a mechanistic explanation of how leaf behaviour influences whole-plant water movement. Transpiration is not merely evaporation from a wet surface, it is biologically modulated water loss from a living organ, and that modulation shapes how strongly leaf demand draws on the water supplied through roots and xylem [9], [10].

The relationship between transpiration, water transport, and mineral movement is therefore best described as linked but non-identical. Mass flow contributes especially to the movement of more mobile nutrients towards roots, and xylem transport can distribute dissolved ions once they have entered the plant. Yet several evidence streams warn against reductionism. Root radial transport depends on pathway structure and membrane transport, xylem conductance can vary with internal properties, and plant-available water must coexist with adequate root aeration for favourable uptake conditions. A clear implication for interpretation is that stronger transpiration can support delivery and redistribution, but it cannot guarantee nutrient acquisition where root transport barriers, ion imbalance, or poor root-zone conditions impose separate limits [1], [7], [8], [11].

V. Practical Implications and Limitations

For hydroponic interpretation, the main practical implication is conceptual rather than prescriptive. Soilless systems make the root zone more visible and controllable, but they do not alter the fundamental requirement that water must still move through roots, vascular tissues, and leaves as one connected pathway. Reviews of hydroponic production emphasise nutrient solution control, root-zone management, dissolved oxygen, and system monitoring, all of which are relevant context for sustaining plant function. However, those sources do not replace physiological explanations of transpiration-driven transport, and they should not be read as evidence that external solution management alone explains internal water ascent. The useful boundary here is that hydroponics changes the growing environment, whereas the plant still relies on its own hydraulic and stomatal mechanisms to move water from the root zone to the shoot [12], [13].

A second implication concerns nutrient movement. Evidence from soilless and hydroponic studies shows that uptake depends strongly on factors such as substrate oxygen status,

nitrate supply, ammonium accumulation, probable microbial immobilisation, recirculation strategy, salinity, solution renewal, and crop demand. These findings are valuable because they prevent a misleading inference that transpiration alone determines how much mineral nutrition a plant acquires. Instead, transpiration should be understood as one contributor to solute transport and xylem delivery within a system that also depends on chemical composition and local root conditions. The limitation of the present evidence base is that it supports a balanced synthesis rather than a single quantified model, so the strongest conclusion is explanatory: transpiration matters greatly for whole-plant water movement, but nutrient uptake remains jointly shaped by hydraulics, root biology, and solution conditions [13], [14], [15].

VI. Conclusion

Water moves through plants by means of a continuous pathway that begins with radial entry at the root, passes into the xylem, and is sustained upward by negative pressure generated at evaporative leaf surfaces. In that pathway, transpiration matters because stomatal water loss helps create the hydraulic demand that links root uptake to leaf function, while stomata simultaneously regulate gas exchange and therefore connect carbon gain to water expenditure. The evidence also shows that mineral movement is related to this flow, particularly through mass movement and vascular transport, but cannot be reduced to transpiration alone because root transport pathways, ion conditions, aeration, and broader nutrient management remain important constraints. A sound understanding of hydroponic plant biology therefore treats transpiration as a driver of integrated water relations across the whole plant, not as a standalone explanation for nutrient uptake or growth [1], [7], [8], [10], [13].

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References

[1] N. Joshi, R. Kaur, and T. Nawaz, "The soil-root nexus: how soil health shapes plant nutrient uptake and food nutritional security," *Plant and Soil*, 2026.

[2] C. Grierson, E. Nielsen, T. Ketelaar, and J. Schiefelbein, "Root hairs," *The Arabidopsis Book*, 2014.

[3] A. Ali, S. J. Jeong, S. Zhen, G. Cocetta, J. Masabni, and G. Niu, "Blue light modulates the interactive effects of far-red light and day-night temperature difference on the growth, morphology and physiology of arugula and lettuce," *Frontiers in Plant Science*, 2025.

[4] J. A. Lankhorst, H. J. de Boer, D. C. Behling, P. L. Drake, E. A. Perkowski, and K. T. Rebel, "Nutrient availability increases photosynthetic capacity without altering the cost of resource use for photosynthesis," *AoB PLANTS*, 2025.

[5] A. Fussy and J. Papenbrock, "An overview of soil and soilless cultivation techniques-chances, challenges and the neglected question of sustainability," *Plants*, 2022.

[6] L. H. Wegner, "Root pressure and beyond: energetically uphill water transport into xylem vessels?" *Journal of Experimental Botany*, 2014. [Online]. Available: https://doi.org/10.1093/jxb/ert391

[7] A. Nardini, S. Salleo, and S. Jansen, "More than just a vulnerable pipeline: xylem physiology in the light of ion-mediated regulation of plant water transport," *Journal of Experimental Botany*, 2011. [Online]. Available: https://doi.org/10.1093/jxb/err208

[8] M. Barberon and N. Geldner, "Radial transport of nutrients: The plant root as a polarized epithelium," *Plant Physiology*, 2014. [Online]. Available: https://doi.org/10.1104/pp.114.246124

[9] S. Azizi, S. Aliniaeifard, S. Zarbakhsh, S. Esmaeili, K. Baghalian, and N. S. Gruda, "Photobiology, photosynthesis, and plant responses under artificial lighting in controlled environment agriculture," *Scientia Horticulturae*, 2025.

[10] Q. Su, Y. G. Park, R. D. Kambale, J. Adelberg, R. Karthikeyan, and B. R. Jeong, "Advancing light-mediated technology in plant growth and development: The role of blue light," *Horticulturae*, 2025.

[11] B. Pragg, M. M. T. Lakshani, T. K. K. C. Deepagoda, K. Cameron, H. Di, T. J. Clough, S. Carrick, B. Elberling, and K. Smits, "Identification of plant soil water and soil aeration corequisites: A management tool," *Soil Science Soc of Amer J*, 2024.

[12] R. S. Velazquez-Gonzalez, A. L. Garcia-Garcia, J. O. Barceinas-Sanchez, E. Ventura-Zapata, and J. C. Sosa-Savedra, "A review on hydroponics and the technologies associated for medium- and small-scale operations," *Agriculture*, 2022.

[13] E. Fathidarehnijeh, M. Nadeem, M. Cheema, R. Thomas, M. Krishnapillai, and L. Galagedara, "Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems," *Canadian Journal of Plant Science*, 2024.

[14] A. Nerlich and D. Dannehl, "Soilless cultivation: Dynamically changing chemical properties and physical conditions of organic substrates influence the plant phenotype of lettuce," *Frontiers in Plant Science*, 2021. [Online]. Available: https://doi.org/10.3389/fpls.2020.601455

[15] M. Elakrouch, M. Mohaddab, A. Rachid, and M. H. Jijakli, "Soilless agriculture at a crossroads: Strengths, challenges, and prospects of hydroponics, aquaponics, and bioponics in relation to precision farming," *Sustainability*, 2026.