Water retention and air-filled porosity

Grant Kinkead
Independent Researcher, Melbourne, VIC, Australia
grant@kinkead.au

***Abstract*—Growing media must provide roots with both retained water and gas-filled pore space, yet these functions are interdependent because water occupies part of the pore network. This paper synthesises evidence on how particle characteristics, pore structure, capillarity, irrigation and drainage shape water retention and air-filled porosity in substrate-based cultivation. The evidence indicates that water-holding capacity alone is an incomplete basis for assessing a medium. Materials differ in bulk density, porosity, air volume and water retention, while their root-zone conditions also change as irrigation fills pores and drainage redistributes or removes water. The resulting trade-off does not imply a universal optimum because the relevant balance depends on substrate properties and management conditions. Drainage state is especially important: as water content falls, gas-filled pore space can increase, but the amount and accessibility of retained water may decline. The paper therefore frames media selection and irrigation as linked decisions rather than independent choices. It concludes that a medium can support roots when its pore structure and water content jointly preserve sufficient retained water and aeration for the intended cultivation conditions [1], [2], [3].**

I. Introduction

Growing media support plant roots through a physical environment in which water and gas occupy the available pore space. Consequently, bulk density, porosity, air volume and water-holding behaviour are not isolated material descriptors. They express how the particles and their arrangement create space that can be occupied by liquid or gas at a particular water content. Reported differences among substrates demonstrate that materials can vary simultaneously in particle-related physical properties, porosity, air volume and water holding. [1] The central challenge is therefore not simply to maximise retained water, but to determine whether the resulting pore occupation leaves an appropriate gas-filled fraction for roots [4].

This issue matters because water retention and air-filled porosity are interacting outcomes rather than independent indicators of growing-medium quality. A medium that retains substantial water may reduce the pore space occupied by gas at a wet state, whereas a more freely draining medium may preserve more gas-filled space while storing less water between irrigations. Evidence across soilless systems indicates that substrate water retention, porosity and aeration vary among materials and require management suited to the particular system. [1] A comparison based only on water-holding capacity can therefore obscure the root-zone conditions experienced after irrigation and during drainage [5].

The relationship can be understood through drainage state. Evidence from soil-root research shows that texture, porosity and bulk density influence water retention and aeration, and that water content and aeration change together as drainage proceeds. [6] Although soils are not interchangeable with engineered growing media, this framework clarifies the physical question addressed here: how can a medium retain enough water for roots without excluding too much air? The paper examines pore structure, saturation and drainage, then synthesises their implications for media assessment and irrigation management [7].

II. Background and Scope

Capillary irrigation research provides a useful starting point because it shows that water movement through a substrate depends on both the medium and the irrigation arrangement. Capillary behaviour, wick dimensions, irrigation timing and substrate coarseness can alter water movement and retention. [8] These observations show that the water state of a growing medium cannot be inferred from its material identity alone. The same medium may experience different water distribution patterns when the supply pathway or timing changes, making its air-filled porosity likewise dependent on the operating condition [9].

Broader soilless-cultivation evidence reinforces the need to distinguish inherent physical characteristics from their expression under management. Substrates differ in porosity, air volume and water-holding properties, and these features respond to irrigation practice. [1] This does not mean that one material property directly determines root performance in all systems. Instead, particle characteristics and pore geometry establish the range of possible water and gas states, while irrigation and drainage determine where within that range the root zone operates. Such interaction limits the value of single-property rankings [10].

The present scope is an explanatory synthesis of water retention and air-filled porosity in growing media, not an evaluation of a particular crop or irrigation technology. Research on soil conditions directly links pore structure, water retention, aeration and drainage with plant-available water and root-zone conditions. [2] That evidence helps define the relevant physical relationships, while the conclusions must be applied cautiously to soilless media because their materials, containers and water-delivery arrangements differ. The remaining gap is a clear account of why the same pore network can hold water and preserve air at different fractions as saturation and drainage change [11].

III. Core Concepts and Mechanisms

Pore structure establishes the physical basis for the water-air balance. Particle size, shape, texture and arrangement determine the void network within a medium and therefore its air-water relations. [3] Water is retained through capillary effects in parts of that network, while pores not occupied by water contribute to air-filled porosity. The important implication is that total porosity alone cannot describe the root environment. Two media with comparable total pore volume may differ in how water is retained and how much pore space remains gas-filled at the same drainage condition.

Water availability and aeration should be treated as co-requirements rather than competing properties that can be optimised independently. Drainage changes matric water content and plant-available water while also changing diffusion-controlled aeration. [2] When water occupies more of the pore network, the connected space available for gas movement is reduced. As water drains, gas-filled space may increase, but continued drainage can also reduce the retained water available to roots. This dynamic explains why an assessment at saturation, immediately after irrigation, or after an extended drying interval can produce different conclusions about the same medium.

The biological relevance of air-filled porosity arises because roots require oxygen for respiration and associated metabolic functions. Low oxygen availability can constrain root metabolism and nutrient uptake, although evidence on plant hypoxia does not itself specify a universal growing-medium threshold. [12] In substrate-based cultivation, porosity, capillarity, oxygenation and water retention are therefore interacting selection criteria. [13] The evidence supports considering these properties together, but it does not justify a single numerical target applicable to all media, crops or irrigation regimes.

IV. Evidence Synthesis

Evidence from hydroponic practice links substrate capillarity, water holding, aeration and irrigation control to changing root-zone conditions. [13] This linkage supports a state-based interpretation of media behaviour. Capillarity influences how water is delivered and retained, while irrigation determines how frequently pores are refilled and drainage determines how much water remains after each event. Air-filled porosity is therefore not fixed simply because the medium composition is fixed. It is a changing fraction that depends on the relation between pore structure and current water content.

Reviews of soilless agricultural systems similarly describe physical properties as determinants of the air-water balance and crop performance. [14] Across substrate classes, the relevant comparison is not whether a medium is categorically wet or aerated, but how its physical structure supports a workable balance under a specified cultivation arrangement. This interpretation helps avoid transferring observations from one material or system directly to another. It also indicates that the value of an apparently favourable property depends on how it interacts with irrigation, drainage and the resulting root-zone state.

The evidence further describes substrate-dependent trade-offs among water holding, aeration, nutrient control and buffering. [14] For the present topic, the key point is that increased retention cannot be assessed without considering the gas-filled pore space left after water redistribution. Conversely, a medium that drains readily cannot be assessed without considering whether retained water remains adequate between irrigations. This is a conditional trade-off, not a universal opposition: the consequences depend on material structure and operating conditions, rather than on a single property measured in isolation.

V. Practical Implications and Limitations

Growing-medium assessment should therefore consider water retention and air-filled porosity at meaningful irrigation and drainage states. Substrate properties and controlled irrigation alter root-zone water and gas conditions, indicating that material selection and irrigation design should be interpreted together. [14] A useful comparison asks how a medium behaves after wetting, during drainage and before the next irrigation, rather than relying only on a maximum water-holding measure. This approach addresses the reader question directly: a medium holds water without excluding excessive air when its pore structure and managed water content leave both retained liquid and gas-filled pathways available.

Container-substrate literature also highlights a practical constraint. Highly porous media can have limited water storage and require irrigation management to control leaching. [15] High porosity is thus not synonymous with a stable root-zone balance. If a medium drains quickly, frequent replenishment may be necessary to maintain water availability, but each irrigation event also changes pore occupation. The suitable operating state must consequently be evaluated in relation to the medium's storage capacity and drainage behaviour, rather than inferred from porosity alone.

Irrigation frequency, substrate capacity and excess application are linked to leaching and changing water conditions. [15] This evidence supports validation of media under the intended irrigation schedule, but it does not provide a universal prescription for watering frequency or an ideal air-filled-porosity value. Further work should compare water content and gas-filled pore space across drainage intervals for specific media and cultivation settings. Such validation would test whether the selected material maintains the required balance across the wetting and drainage cycle rather than only at one measurement point.

VI. Conclusion

Water retention and air-filled porosity are best understood as complementary but interacting expressions of pore structure and water content. Particle arrangement and capillary behaviour determine how water is retained, while irrigation and drainage continually alter the fraction of pore space occupied by water or gas. [2], [3] A growing medium should therefore

not be judged by water-holding capacity alone. Its suitability depends on whether the managed drainage state preserves retained water for roots while maintaining adequate gas-filled pore space.

The available evidence supports a system-specific approach to media selection and irrigation management. Differences among substrates, together with changing root-zone conditions over irrigation cycles, preclude a universal optimum for the water-air balance. [1], [13], [14] The highest-value next step is to validate candidate media under their intended irrigation and drainage conditions, assessing water retention and air-filled porosity together rather than treating either as a standalone quality measure.

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REFERENCES

[1] A. Tuxun, Y. Xiang, Y. Shao, J. E. Son, M. Yamada, S. Yamada, K. Tagawa, B. Baiyin, and Q. Yang, "Soilless cultivation: Precise nutrient provision and growth environment regulation under different substrates," *Plants*, 2025.

[2] 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.

[3] G. Barrett, P. Alexander, J. Robinson, and N. Bragg, "Achieving environmentally sustainable growing media for soilless plant cultivation systems - a review," *Scientia Horticulturae*, 2016.

[4] I. Szekely and M. H. Jijakli, "Bioponics as a promising approach to sustainable agriculture: A review of the main methods for producing organic nutrient solution for hydroponics," *Water*, 2022.

[5] S. Scott and C. Villouta, "Dissolved oxygen limitation and pythium root rot in strawberry nft systems: Mechanisms, research gaps, and prospects for substrate-free production," *Frontiers in Plant Science*, 2026.

[6] 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.

[7] 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," *Can. J. Plant Sci*, 2024.

[8] N. P. K. Semananda, J. D. Ward, and B. R. Myers, "A semi-systematic review of capillary irrigation: The benefits, limitations, and opportunities," *Horticulturae*, 2018.

[9] B. M. Eldridge, L. R. Manzoni, C. A. Graham, B. Rodgers, J. R. Farmer, and A. N. Dodd, "Getting to the roots of aeroponic indoor farming," *New Phytologist*, 2020.

[10] 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.

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

[12] J. Jethva, R. R. Schmidt, M. Sauter, and J. Selinski, "Try or die: Dynamics of plant respiration and how to survive low oxygen conditions," *Plants*, 2022.

[13] 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.

[14] I. A. Lakhiar, H. Yan, T. N. Syed, C. Zhang, S. A. Shaikh, M. Rakibuzzaman, and R. B. Vistro, "Soilless agricultural systems: Opportunities, challenges, and applications for enhancing horticultural resilience to climate change and urbanization," *Horticulturae*, 2025.

[15] J. C. Majsztrik, R. T. Fernandez, P. R. Fisher, D. R. Hitchcock, J. Lea-Cox, J. S. Owen, Jr., L. R. Oki, and S. A. White, "Water use and treatment in container-grown specialty crop production: A review," *Water, Air, & Soil Pollution*, 2017.