Physical properties of hydroponic growing media

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

***Abstract*—Hydroponic growing media influence root-zone behaviour through their physical structure rather than through material labels alone. Particle size, bulk arrangement and pore distribution determine the balance between mechanical root support, water retention, drainage and air-filled space. This paper synthesises evidence on the physical properties used to describe growing media and explains how these properties interact to shape fluid movement and root conditions. The evidence indicates that porosity, capillarity, texture and available water are interdependent characteristics of a pore network, requiring media to be considered as structured root-zone environments rather than as generic materials. It also shows that processing, source and particle-size distribution can alter physical behaviour within a nominal material category. Consequently, material selection should assess the physical characteristics of a specific grade or mix, particularly its pore structure and resulting air-water balance. The review identifies the need for condition-specific physical characterisation because evidence from broader soilless and root-zone literature does not always isolate the behaviour of individual particulate media.**

I. Introduction

Hydroponic cultivation can use a solid growing medium to hold roots in position while allowing water and dissolved nutrients to move through the root zone. In this setting, the medium is not merely an inert container filling. Its physical properties determine the space occupied by solids, water and air, and therefore influence the conditions surrounding roots. Reviews of soilless cultivation identify substrate physical properties and the associated air-water balance as central features of substrate-based production systems [1]. The practical implication is that root support and water supply cannot be considered separately: both arise from the same bulk structure. A useful assessment must therefore focus on how the medium is arranged and how its pore network behaves under wet conditions [2].

The major physical properties of hydroponic growing media include particle size and texture, bulk structure, total pore space, pore distribution, water retention, drainage and air-filled space. These descriptors are connected rather than independent. A medium that holds more water after drainage may have less pore volume occupied by air, while a structure that drains readily may provide a different level of water storage and capillary continuity. Existing accounts of soilless substrates characterise their physical performance through these air-water relations [1]. This relationship makes physical characterisation important because a label such as coir, bark or fibre does not by itself state how a particular product will behave around roots.

This paper examines which physical properties determine how a hydroponic growing medium behaves around roots. It argues that a growing medium is defined operationally by its structure and pore network, because these features govern root support, water storage, drainage and air-filled space. The discussion first establishes the scope of physical properties, then explains the mechanisms linking particle structure to fluid behaviour, synthesises evidence on variation within material categories, and considers implications for assessing individual media grades. This focus is necessary because substrate choice, source and physical properties can jointly affect performance [1].

II. Background and Scope

The physical behaviour of a growing medium can be understood through the relationship between texture, structure and pore space. Texture describes the size-related character of constituent particles, whereas structure concerns their arrangement in the bulk medium. Together, these features establish the geometry through which water is retained, drained or redistributed, and through which air remains available after wetting. Work on root-zone conditions links texture and structure to water-air relations and root conditions [3]. Although this evidence includes soil-root systems, its conceptual value for hydroponic media lies in showing that roots experience a physical environment created by pore architecture rather than by material identity alone.

A nominal material category is therefore an incomplete predictor of physical performance. Two media described by the same material name may differ in particle-size distribution, processing history, compaction tendency or bulk arrangement. Such differences can alter the balance between smaller pores that retain water and larger pores that contribute to drainage and aeration. Evidence on texture and structure indicates that water and aeration behaviour change beyond what can be inferred from nominal material identity [3]. The limitation is that broad material classifications can obscure the characteristics most relevant to a specific root zone, making generic recommendations less reliable than measurements or descriptions of the actual grade used.

The scope of this paper is confined to physical characteristics that influence root support, water movement and air space. Porosity, capillarity and oxygenation are relevant because they connect the medium's solid framework to the water and air conditions experienced by roots [4]. Chemical composition, nutrient formulation and biological processes are outside the main analysis except where the supplied evidence shows that

physical properties cannot be interpreted independently of the root-zone environment. This boundary allows the paper to address the central explanatory gap: how particle structure and pore distribution provide a more useful basis for understanding medium behaviour than material labels alone.

III. Core Concepts and Mechanisms

Particle size is a primary structural feature because it contributes to the dimensions and connectivity of pores formed between particles. Particle-size-dependent properties can therefore influence substrate performance, including the relative tendency to retain water or maintain open air pathways [4]. This does not imply that particle size acts alone. Particle shape, packing and the range of sizes in a medium also influence the bulk structure. Nonetheless, particle size is an accessible indicator of how the physical framework may change between grades. Its engineering significance is that a shift in grade can change root-zone behaviour even where the nominal substrate material remains unchanged.

Porosity describes the volume of the medium not occupied by solid material, but total pore space alone does not explain root-zone function. Pore distribution matters because water retention and drainage depend on the sizes and arrangement of pores, while air-filled space emerges as water leaves part of that pore network. Reviews of soilless systems consistently treat physical and air-water properties as linked aspects of substrate performance [5]. Capillarity provides the mechanism by which water can be held within smaller pores, whereas larger or more continuous pores can support drainage and gas exchange. The resulting balance is a property of the assembled medium, not simply a fixed property of its constituent material.

Root support is likewise a structural function. The solid fraction provides a framework that anchors roots, while pore space permits water and air to coexist around them. Evidence from container-grown production connects substrate porosity and available water with irrigation, aeration and crop support [6]. This connection means that irrigation cannot be evaluated independently from medium structure: the same watering input may yield different water and air conditions in media with different pore networks. The available evidence supports this systems relationship, but it does not supply universal physical thresholds for all hydroponic media, crops or operating conditions. Assessment should therefore relate physical descriptors to the particular medium and root-zone setting.

IV. Evidence Synthesis

Across the evidence base, variation within material categories is a recurrent reason to avoid treating material names as performance specifications. Reviews of container substrates discuss differences in quality, processing and particle size within categories that may otherwise appear comparable [6]. These differences matter because processing can change the composition and arrangement of particles, thereby altering porosity and the distribution of water- and air-containing pores. A product described as a particular fibre, bark or organic substrate may consequently behave differently from another product with the same broad label. The implication is that selection decisions should identify the physical grade and bulk condition of a medium, rather than relying on nominal material type as a proxy for root-zone performance.

The growing-media literature provides a coherent explanation for this variation by directly linking structure, particle size, texture and air-water relations [7]. A medium's physical performance arises from the interaction of its particles rather than from a single characteristic. Fine and coarse fractions, for example, must be interpreted as components of a distribution that shapes packing and pore geometry. This synthesis helps explain why a medium can offer apparent water storage while still differing substantially in drainage or aeration from another medium of similar origin. It also indicates that physical descriptors should be considered together, because a change in one structural feature can modify several root-zone functions simultaneously.

Evidence also directly associates particle size and structure with porosity, water retention and aeration [7]. This association supports a practical hierarchy for interpretation: particles and their arrangement form the bulk structure; bulk structure creates a pore distribution; pore distribution governs water retention, drainage and air-filled space; and these conditions influence root support and the root-zone environment. The hierarchy is useful because it distinguishes causes from outcomes. However, it should not be treated as a simple one-directional rule. The same particle-size description can produce different outcomes when packing, processing or source characteristics differ, so direct physical assessment remains preferable to assumptions based on a label.

V. Practical Implications and Limitations

The physical assessment of a growing medium should therefore begin with the specific product or mix rather than with its nominal material category. This is especially important for materials such as wood fibre, where a common label can conceal variation in processing, quality and particle size [7]. The relevant question is not whether a material name is generally associated with a particular behaviour, but whether the supplied grade creates the pore structure required for the intended root zone. This approach reduces the risk of transferring expectations from one product to another without recognising structural differences. It also frames product comparison as an examination of physical behaviour, including water storage, drainage and air-filled space.

Porosity, water holding and aeration should be interpreted as a connected physical set rather than as isolated selection criteria. Soilless cultivation reviews identify these properties as important features of substrate-based systems [8]. A medium with a favourable value for one property may still require closer consideration of the associated pore distribution and water-air balance. For example, water holding is meaningful only in relation to how much pore space remains air-filled after drainage, while drainage must be interpreted in relation to retained water and structural support. The evidence supports

this integrated approach, but it does not establish a single optimal combination that applies across all media and production circumstances.

The available evidence also limits the precision of generalisations. Root-zone fluid and root-interaction concepts are supported by research in systems that do not directly examine particulate growing media [9]. In addition, broader soilless literature may identify substrate requirements without comprehensively resolving every physical property of a particular medium [10]. Consequently, future validation should characterise specific media grades and examine their pore-related water and air behaviour under relevant operating conditions. This is not a call for universal prescriptions. Rather, it recognises that the physical properties most useful for prediction are those measured or clearly specified for the medium actually placed around roots.

VI. Conclusion

Hydroponic growing media behave around roots according to their bulk structure and pore network. Particle size, texture, packing, porosity and pore distribution collectively determine root support, water retention, drainage and air-filled space. The reviewed evidence consistently links substrate physical properties to air-water balance and root-zone conditions [1], [7], [8]. Material type remains relevant as a broad description, but it does not adequately predict performance when product source, processing or particle-size grade differs. The strongest basis for interpretation is therefore an operational view of the medium as a structured environment in which solids, water and air are distributed through connected pores.

The highest-value next work is condition-specific physical characterisation of individual media grades and mixes. Such assessment should examine how particle structure and pore distribution correspond to water holding, drainage and aeration in the intended root-zone context. This need follows from evidence that substrate-dependent behaviour can differ across otherwise comparable mixes [11] and that root-zone conditions depend on linked physical properties [6]. A more explicit description of the actual medium will support clearer comparison, more defensible selection and more reliable interpretation of root-zone behaviour.

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