Selecting media according to system design

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

***Abstract*—Growing media should be selected as part of root-zone system design rather than as an isolated material choice. This paper examines how the physical behaviour of media should complement the way a hydroponic system supplies water, nutrients and air. Evidence indicates that capillary delivery depends on the interaction of substrate properties with container scale, crop demand and flow conditions, while root-zone oxygen is constrained by water-filled pore space and gas diffusion. Media texture and structure therefore affect the balance between moisture retention, drainage and aeration, but their performance cannot be separated from irrigation scheduling, container geometry and root-zone exposure. The synthesis compares capillary, drip-fed, nutrient-film, water-culture and aeroponic delivery contexts to show why a medium that performs adequately in one configuration may be unsuitable in another. It concludes that universal media-selection rules are not scientifically defensible because crop, cultivar, container geometry, irrigation regime and environmental conditions alter the relevant design balance. Media selection should instead begin with delivery mode and root-zone conditions, followed by validation under the intended crop and operating configuration [1], [2], [3], [4].**

I. Introduction

Growing media are often described by their individual properties, such as water retention, porosity or structural stability. However, those properties become agronomically meaningful only within the delivery conditions imposed by a cultivation system. Capillary irrigation illustrates this dependence: wicks, capillary mats and ebb-and-flow arrangements rely on movement of water through or into the medium, so media capillarity contributes directly to whether roots receive water between irrigation events. A material that maintains a suitable moisture distribution under one capillary arrangement may not do so when the hydraulic path, container depth or replenishment pattern changes. Selection should therefore begin by asking how water reaches, drains from and is retained around the root zone, rather than by treating a medium as universally suitable [1], [2].

The importance of this systems view is reinforced by evidence that crop responses differ across substrate and soilless production configurations. Substrate choice interacts with crop requirements and the cultivation environment, meaning that apparent material performance cannot be assumed to transfer unchanged between crops or facilities. This does not imply that media properties are unimportant. Instead, it positions them as design variables that must be matched with the root-support and delivery environment. The central problem is consequently one of compatibility: a medium must support the water, nutrient and air conditions created by the system, without being expected to correct a fundamentally unsuitable irrigation or drainage arrangement [3], [5].

Capillary irrigation research also cautions against simple prescriptions because performance varies with pot size, crop, flow conditions and substrate characteristics. Such variation is especially relevant where media are expected to redistribute water over a vertical or horizontal distance. The same material can face a different hydraulic demand when container dimensions alter the pathway between supply and roots, or when crop water use changes the rate at which stored water is depleted. This paper develops a system-matching framework for interpreting these interactions. It first defines the relevant scope and media behaviours, then synthesises evidence across delivery contexts before identifying practical constraints and validation needs [1], [6].

II. Background and Scope

Existing work on soilless cultivation shows that outcomes are shaped by combinations of crop, substrate, cultivar and environment. This evidence limits the value of choosing media through broad labels alone, such as moisture-retentive or free-draining. Those labels describe tendencies, but they do not establish whether the resulting root-zone conditions will be suitable for a particular crop within a particular delivery arrangement. A useful selection process must therefore distinguish between inherent material characteristics and the conditions produced after the material is placed in a container, irrigated and colonised by roots. The scope here is that interaction, not a ranking of media or a recommendation of a single material for all hydroponic systems [3], [7].

The relevant physical basis is the water-aeration balance created by texture, structure and the design of an engineered growing medium. Texture and particle arrangement influence pore characteristics, while structure affects how water is held and how air-filled pathways remain after irrigation or drainage. These properties influence root-zone conditions, but they do not operate independently of system design. A medium with a high capacity to retain water may be advantageous where supply is intermittent and drainage is effective, yet it may sustain excessive wetness if the delivery pattern already keeps the root zone close to saturation. Conversely, a coarse medium may require a delivery pattern capable of meeting demand without sacrificing aeration [8], [9].

Water-aeration behaviour also changes with irrigation and drainage, so an assessment based only on a dry material description is incomplete. Irrigation duration, frequency and placement determine the wetting pattern, while drainage

boundaries and container geometry shape where water persists. This creates a design gap in many universal selection rules: they assume that a medium has one stable performance profile, although the operational root zone is produced jointly by material properties and hydraulic management. A defensible framework must evaluate the medium under the intended irrigation regime and physical containment conditions, with attention to the resulting balance rather than to an isolated property target [8], [10].

III. Core Concepts and Mechanisms

In drip-fed configurations, the delivery infrastructure is part of the media-selection problem because water quality can affect emitter function. Irrigation-water characteristics are associated with clogging risks in micro-irrigation systems, potentially changing the volume and distribution of water supplied to the container. When delivery uniformity is altered, the planned relationship between medium retention and irrigation timing is altered as well. A media choice that depends on precise, repeated wetting may therefore be less robust where filtration, water treatment or emitter maintenance cannot sustain the intended flow behaviour. The implication is not that media should compensate for poor infrastructure, but that the achievable delivery precision must be included in the matching assessment [11], [12].

In nutrient-film systems, root-zone exposure is influenced strongly by channel geometry and root development rather than by a bulk medium. Evidence from strawberry systems links channel geometry and root mats with oxygen transfer and production outcomes, demonstrating that physical root-zone conditions can shift as roots occupy the available channel space. Where a small amount of support material is used, its role should be interpreted against this exposure pattern. A highly retentive medium may hold water around roots that otherwise experience substantial air exposure, whereas a limited-support configuration may need to preserve root anchorage without obstructing the intended film-based exchange. The relevant question is how the medium modifies the established water and air pathway [13].

The nutrient-film evidence also shows why universal oxygen thresholds or media rules are difficult to apply. Geometry and crop duration affect root-mat development and associated oxygen conditions, so the same nominal delivery mode may produce different root-zone environments over time. This temporal dimension matters for media selection because an initially acceptable material and container arrangement may behave differently as root volume increases. Selection should therefore include the expected crop duration and root occupation of the growing space, rather than relying only on conditions observed immediately after planting. The evidence supports a conditional approach to oxygen management, not a single transferable target for all channel and crop combinations [13].

IV. Evidence Synthesis

Comparisons among substrate-based culture, water culture and aeroponics indicate that crop-system compatibility is central to successful root-zone design. These approaches provide distinct patterns of contact between roots, nutrient solution and air. A support medium is consequently most relevant where it shapes water storage, plant anchorage or drainage, whereas its role differs in systems where roots are primarily exposed to solution or droplets. Aeroponic delivery, for example, is associated with root-zone oxygen conditions that depend on droplet delivery and system operation. The media-selection task is therefore not to impose a preferred substrate across all systems, but to determine whether a medium assists or disrupts the delivery environment required by the selected configuration [14], [15].

The available evidence does not support a single best system or a single best medium across crops, locations and production contexts. Differences in crop response arise because the relevant constraints change with the root-support arrangement, environmental conditions and production objectives. This finding has an important methodological consequence: comparisons between media must specify the delivery mode, crop and operating conditions before their conclusions can be applied elsewhere. A medium that succeeds in a containerised system with managed drainage should not be assumed to be equally appropriate for a water-culture or aeroponic arrangement, where water contact and oxygen exposure are governed by different mechanisms [14], [15].

Container production research further connects irrigation precision, filtration, water use and runoff with the management of root-zone conditions. For media-based hydroponics, this supports treating container and irrigation design as an integrated control boundary. The medium determines part of the storage and flow response, but filtration and delivery precision influence whether each container receives the intended irrigation event, while drainage influences the fate of excess solution. Consequently, a media decision should be tested against actual distribution and runoff behaviour rather than judged solely by nominal physical characteristics. This is particularly important where a material's suitability depends on narrow timing or volume assumptions [16].

V. Practical Implications and Limitations

A practical system-matching process should assess container geometry and irrigation timing together. Geometry influences the path through which water is distributed and drained, while timing determines how often the medium must buffer water between applications. Evidence from container-grown production associates these conditions with treatment performance, indicating that an irrigation strategy cannot be transferred without regard to the physical dimensions that contain the roots and medium. The appropriate question is therefore whether the selected medium creates an acceptable moisture and aeration pattern at the intended container size and irrigation interval. This framing avoids selecting a material

on the assumption that its performance is independent of its installed geometry [16].

Growing-media research directly identifies irrigation regime and container geometry as determinants of media performance. This supports a staged selection procedure: first characterise the system's water-delivery and drainage pattern; next identify the required degree of retention, drainage and structural support; then assess candidate media under the intended geometry and crop. Such a procedure does not produce a universal list of preferred materials, because the relevant balance changes with configuration. Its value lies in making the design assumptions visible and testable. Where a candidate medium requires irrigation conditions that the system cannot reliably provide, changing the medium alone is unlikely to resolve the mismatch [4].

The limits of generalisation are substantial. Media behaviour is affected by material properties, container geometry, irrigation regime, crop requirements and commercial conditions, so recommendations require validation within the proposed production setting. Current evidence supports the framework of matching, but it does not justify fixed rules that prescribe one medium for every crop or delivery mode. Further validation should examine root-zone responses across intended crop durations, container dimensions and operating schedules, particularly where changes in root development can alter water and air pathways. This need for contextual testing is a design requirement, not an indication that material properties can be ignored [4].

VI. Conclusion

Media selection is best understood as a compatibility decision between material behaviour and system design. Capillary delivery, container geometry, irrigation timing, drainage, root development and root-zone exposure jointly determine whether a medium supports the intended balance of water and air. The evidence shows why a medium suitable in one system may behave differently in another, and why neither material labels nor universal rules can replace system-specific assessment. A sound choice complements the established irrigation, drainage and exposure pattern rather than attempting to compensate blindly for deficiencies in that pattern [1], [4], [8], [13].

The highest-value next step is validation under the intended crop, container geometry and irrigation regime. Such testing should assess whether the installed medium produces the expected root-zone conditions as the crop develops, while confirming that delivery infrastructure can maintain the planned irrigation distribution. This evidence-based approach preserves the distinction between selecting a suitable root-support material and redesigning an unsuitable delivery system [4], [11], [16].

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