How Hydroponics Replaces Soil Functions

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***Abstract*—Hydroponics is often described as cultivation without soil, yet plant growth in these systems still depends on the same root-zone requirements that govern growth in soil. This paper explains hydroponic performance through the principle of functional substitution: hydroponic systems succeed not by escaping plant biology, but by deliberately replacing or tightly regulating the functions that soil commonly provides. Drawing on recent literature in plant nutrition, soilless cultivation, root-zone aeration, substrate behaviour, and nutrient-solution management, the paper shows that soil ordinarily contributes several interconnected services, including nutrient buffering, water retention, aeration, structural support, and biologically mediated transformations that affect nutrient availability. Hydroponic systems can substitute for many of these services by supplying prepared nutrient solutions, controlling water delivery, preserving oxygen access, and using substrates or engineered media to stabilise roots and the immediate rhizosphere. At the same time, some functions are not truly replaced by a soil analogue, but are instead met through a different pathway, such as direct chemical control rather than reliance on native soil processes. The evidence indicates that removing soil does not remove the plant's physiological constraints. Rather, hydroponics relocates responsibility for meeting those constraints from the field soil to system design and management, which clarifies both its effectiveness and its practical limits.**

I. Introduction

Soil is not merely a place that holds roots. It is a complex root-zone environment that influences nutrient exchange, water availability, and biological interactions that shape plant uptake. Recent work describes soil organic matter as a widely used indicator of soil health because it improves cation exchange capacity, increases water retention, and supports microbial biodiversity, all of which can affect nutrient bioavailability and plant access to resources [1]. This matters for understanding hydroponics because the central question is not whether plants can ignore these functions once soil is removed, but whether a hydroponic system can provide them by other means. An authoritative account of hydroponics therefore has to begin from soil function, not from the misleading idea that hydroponics bypasses normal plant requirements [2].

Evidence from plant physiology reinforces that point. Experimental work on nutrient availability across sand and natural soils found that higher nutrient availability increased photosynthetic capacity and reduced the carbon costs of nitrogen acquisition, even though some aspects of resource-use behaviour remained stable across treatments [3]. The implication is that plant performance still responds to root-zone supply conditions, regardless of whether those conditions occur in a conventional soil or a simplified growth medium. Hydroponics can therefore only succeed if it satisfies the same fundamental biological requirements that support carbon gain, nutrient acquisition, and growth in soil. Removing soil changes the delivery mechanism, but it does not remove the dependence of leaves, roots, and metabolism on adequate root-zone conditions.

A further reason for caution is that plant response depends not only on supplying nutrients, but also on matching supply form and availability to species-specific demand. In vitro evidence shows that plant species can differ markedly in tissue mineral accumulation, nutrient recovery, and effective use of supplied media, even when nutrients are initially present in dissolved and apparently bioavailable forms [4]. This paper uses that principle to explain hydroponics through functional substitution. It argues that hydroponic cultivation works when it deliberately replaces the essential functions that soil would otherwise help provide, including nutrient delivery, water supply, aeration, and root support. It also distinguishes true substitution from pathway change, where the same plant requirement is met through a more direct engineered route rather than through soil-mediated processes.

II. Background and Scope

The literature on soilless cultivation shows that removing soil does not produce a single uniform model of plant growth. Instead, it produces a family of approaches that differ in how they reconstruct the root environment. This is clear in work on bioponics, where organic nutrient solutions are generated through several distinct processing pathways, including tea-type extraction, aerobic microbial degradation, anaerobic digestion, and combined anaerobic-aerobic degradation [5]. These categories matter because they illustrate that even within soil-free cultivation, nutrient supply can still depend on biological transformation, chemical release, and management choices. The scope of this paper is therefore not a comparison of named hydroponic systems, but an explanation of how soil functions are replaced or re-routed within the root zone when soil itself is no longer the primary medium.

Recent reviews define soilless cultivation as the artificial regulation of the root environment in order to create favourable conditions for growth, particularly through the control of nutrient supply, gas exchange, and microbial communities [6]. That framing is especially useful for the present topic because it shifts attention from equipment to function. A hydroponic system is successful to the extent that it recreates the conditions required for root operation, not simply to the extent that it circulates water or fertiliser. This provides the conceptual gap addressed in this paper. Popular descriptions

often present hydroponics as a replacement for soil itself, whereas the stronger scientific interpretation is that hydroponics replaces selected soil functions and directly manages others. That distinction is essential for answering how plants continue to receive what they need once soil is removed.

The importance of this functional perspective is also evident in studies of root-zone aeration. Soil research examining pasture profiles highlighted the combined requirement for soil water and diffusion-controlled aeration in the root zone [7]. In other words, successful rooting environments must maintain both moisture and oxygen access, rather than maximising one at the expense of the other. This paper adopts that biological constraint as part of its boundary. It does not treat hydroponics as an unrestricted improvement over soil, nor does it broaden into unrelated questions of automation or broad sustainability policy. Its purpose is narrower and more explanatory: to show which root-zone functions soil commonly performs, how hydroponics deliberately substitutes for them, and where hydroponics instead changes the pathway by which plants obtain the same essential requirements.

III. Core Concepts and Mechanisms

The first core concept is that plants require access to mineral nutrients according to biological function, not according to the presence of soil. A recent discussion of plant nutrition proposes that a plant nutrient should be understood as an element that is essential or beneficial for growth, development, or harvested-product quality in a given species and environment [8]. This definition is helpful because it disconnects nutrient necessity from any single cultivation medium. Soil is one context in which these elements become available, but it is not the reason plants need them. Hydroponics therefore substitutes for one major soil function by providing required mineral elements in prepared solution. However, that substitution remains constrained by species, developmental stage, and environment, so hydroponics cannot rely on generic nutrient presence alone. It must supply nutrients in forms, concentrations, and conditions that roots can actually use.

The second core concept is that hydroponics is not a denial of rooting, but a reorganisation of rooting conditions. Hydroponics has been described as a soilless horticultural method in which plants grow on natural or manufactured substrates while roots extract nutrients from a prepared nutrient solution [9]. This definition captures the functional substitution principle directly. Soil usually combines structural support, water holding, and nutrient contact in one heterogeneous medium. Hydroponics separates these roles and redistributes them across solution chemistry, container design, irrigation control, and, in some cases, inert or semi-inert substrates. Where soil once acted as a mixed physical and chemical environment, hydroponics creates an engineered root zone. The requirement being met remains the same, but the pathway is often more explicit and more dependent on system management.

A third concept concerns why this distinction has wider relevance without changing the paper's biological focus. Reviews of soilless agriculture describe resilience in terms of a food system's capacity to absorb and adapt to stress while maintaining productivity, resource efficiency, and ecological balance [10]. That broader framing does not prove that hydroponics is always superior, but it helps explain why controlled root-zone substitution attracts interest. By decoupling crop production from degraded or limited soils, hydroponics can shift some vulnerabilities away from field conditions and towards managed infrastructure. Even so, resilience is not created simply by removing soil. It depends on whether the engineered system continues to meet plant needs for nutrition, water, oxygen, and support under variable conditions. The mechanism of success remains biological compliance, not technological exemption.

IV. Evidence Synthesis

Across the literature, soilless plant culture is consistently defined by the absence of soil as the rooting medium, while roots are typically retained within a porous substrate or related growing medium [11]. This supports a precise interpretation of functional substitution. Hydroponics does not necessarily eliminate the need for a local physical environment around the roots. Instead, it removes the field soil and reconstructs a simplified rhizosphere in which water, dissolved ions, and oxygen can be managed more directly. In that sense, hydroponics truly substitutes for some soil functions, such as storing and delivering water near roots, while it changes the pathway for others, such as nutrient buffering and supply. Rather than depending on naturally variable soil chemistry, the system supplies nutrient availability through formulation and monitoring. The plant still experiences a root environment, but one with different sources of control.

Evidence from substrate studies strengthens this distinction by showing that material choice still matters after soil removal. A study comparing dried sphagnum moss, wood chips, and hemp fibres against rockwool for lettuce in soilless greenhouse cultivation demonstrates that alternative substrates can differ in their physical and chemical behaviour [12]. This means hydroponic systems do not simply replace soil with empty space. When substrates are used, they continue to influence water retention, aeration, and the immediate chemical conditions surrounding roots. The implication is that some hydroponic designs substitute for the structural and hydraulic roles of soil through engineered media rather than through bare solution alone. Yet this is still not a bypass of plant biology, because roots remain sensitive to the same balance among moisture, oxygen, and contact conditions that governs performance in soil-based systems.

The broader synthesis literature frames soilless cultivation as especially useful where soils are degraded or water is limited, and it links these systems to food-security concerns and environmentally oriented production strategies [13]. For the present paper, the most important point is not the broad promise itself, but what that promise depends on. Soil-free cultivation becomes credible in poor-soil settings only if the system can reproduce the essential root-zone functions that damaged soil no longer provides reliably. Hydroponics

therefore works as a substitution strategy precisely because it relocates critical processes from uncertain field conditions to controlled inputs and environments. At the same time, this evidence base does not justify treating hydroponics as independent of biological limits. It shows instead that careful substitution can preserve plant function under conditions where natural soil performance is constrained or inconsistent.

V. Practical Implications and Limitations

In practical terms, hydroponics replaces soil's nutrient-supply role most clearly through direct delivery of a nutrient-rich water solution to the roots. Reviews describe hydroponics as allowing control of nutrient levels, efficient water use, and cultivation where soil quality is poor [14]. This is a genuine substitution for one of soil's central agronomic functions, namely providing a medium from which roots obtain dissolved mineral elements and water. However, direct delivery also changes the pathway by which this requirement is met. Instead of relying on a complex soil matrix to retain, exchange, and slowly release nutrients, hydroponics depends on deliberate formulation and management. The practical implication is that greater control can improve consistency, but only when operators maintain the chemical environment within biologically acceptable bounds.

Reported productivity and water-use outcomes illustrate both the attraction and the caution required in interpreting hydroponic performance. One recent review reports that soilless systems can achieve leafy-vegetable yields 200 to 300 per cent above open-field cultivation while reducing water consumption by 80 to 95 per cent [15]. These figures support the idea that functional substitution can be highly effective when root-zone conditions are tightly managed. Yet the numbers should not be read as evidence that hydroponics removes plant constraints. Rather, they indicate that growth can respond strongly when the root environment is regulated more precisely than in many open-field contexts. The limitation is that such reported gains depend on crop type, system design, and management quality, so they cannot be generalised as an automatic consequence of removing soil alone.

A further limitation is that hydroponic success may trade one set of constraints for another. Reviews of nutrient-solution management report significantly higher yields than conventional agriculture in many cases, but also note higher energy consumption and the importance of solution composition for achieving efficient nutrient and water use [16]. This highlights an important boundary for the substitution argument. Hydroponics can replace several beneficial functions of soil, but it also transfers responsibility for maintaining those functions to infrastructure, monitoring, and operational decisions. The system still has to preserve nutrient adequacy, oxygen access, and hydraulic stability, and failure in these controls can rapidly affect crops because there is less buffering than in many field soils. The main validation need is therefore not proof that plants can grow without soil, but evidence that the engineered root zone can remain reliably within biological limits across real production conditions.

VI. Conclusion

Hydroponics replaces soil functions by reconstructing the root environment around the same underlying biological requirements that apply in soil. The evidence reviewed here shows that soils ordinarily contribute nutrient availability, water retention, aeration, structural support, and biologically mediated root-zone conditions, while hydroponic systems meet these requirements through prepared nutrient solutions, controlled water delivery, engineered substrates, and deliberate regulation of the rhizosphere [1], [6], [11]. This explains why hydroponics works without implying that soil has become irrelevant to plant biology. The central principle is functional substitution: hydroponics succeeds when it supplies what soil would otherwise help provide, and fails when those root-zone requirements are neglected.

The paper also clarifies that substitution is uneven. Some functions are directly replaced, such as nutrient and water supply, while others are met through a changed pathway, such as chemical control instead of native soil buffering or microbial processing [5], [14]. Removing soil therefore does not remove biological constraints. It makes them more visible and, in many cases, more dependent on precise management. The highest-value next work is continued validation of how nutrient formulation, aeration control, and substrate behaviour interact across species and production settings, so that claims about hydroponic performance remain tied to the root-zone mechanisms that actually support plant growth [4], [12], [16].

Acknowledgment

The author used artificial intelligence tools to assist with manuscript drafting and revision, and with LaTeX and bibliography preparation. The author reviewed all AI-assisted output and remains responsible for the final content.

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