What Soil Normally Provides

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***Abstract*—Soil is often treated as the default medium for plant growth, yet its importance lies in the services it provides to roots rather than in any intrinsic biological requirement for soil itself. This paper explains those services as a functional root-zone package: physical support, water storage and delivery, nutrient storage and exchange, pore space for gas movement, chemical buffering, and biologically mediated transformations that influence nutrient availability. Drawing on recent literature in soil science, plant nutrition, and soilless cultivation, the paper argues that conventional soil integrates these functions in a coupled and spatially variable environment, whereas soilless systems separate, simplify, or directly control selected functions through nutrient solutions, substrates, and environmental regulation. The evidence indicates that plants can maintain mineral nutrition and productive growth when these root-zone functions are supplied by other means, including prepared nutrient solutions and porous media, but the substitution is selective rather than total. Some soil services, such as anchorage and immediate nutrient delivery, can be reproduced directly, while others, such as buffering and biologically complex transformations, are managed differently or reduced in scope. The practical implication is that soil should be understood as a multifunctional system for root support and regulation, and that comparisons with hydroponics are most accurate when made at the level of function rather than medium.**

I. Introduction

In conventional plant growth, soil does far more than hold roots in place. It acts as an integrated root-zone environment in which physical structure, water retention, nutrient exchange, and biological activity interact to influence plant access to resources. Recent work on the soil-root nexus presents soil organic matter as a widely recognised indicator of soil health because it strengthens cation exchange capacity, improves water retention, and supports microbial biodiversity, all of which can affect nutrient bioavailability and uptake [1]. This framing is important because it shifts attention away from soil as a substance and towards soil as a set of linked functions. The implication is that the agronomic value of soil lies in the services it delivers to roots, although the exact contribution of each service can vary with soil condition and management [1], [2].

Evidence from plant physiology also supports a functional interpretation of the root environment. A greenhouse study comparing sand and natural soils across nutrient availability levels found that increasing nutrient availability raised photosynthetic capacity and lowered the carbon costs of nitrogen acquisition, while leaf ci/ca remained unchanged across treatments [3]. For the present topic, the important point is not the specific experimental system, but the demonstration that plant performance responds strongly to how the root zone supplies nutrients. Soil therefore matters because it influences access costs and supply conditions, not because plants require contact with soil particles as such [3]. At the same time, this evidence does not imply that all growth responses can be reduced to nutrient concentration alone, because natural soils also combine water, aeration, and buffering processes that were not identical to sand in a broader ecological sense.

Further support for this interpretation comes from in vitro nutrition research showing that plant mineral status depends on the form, availability, and utilisation of supplied nutrients rather than on the presence of soil itself. In one study, four plant species grown on Murashige and Skoog medium showed species-specific patterns of tissue mineral accumulation, nutrient utilisation efficiency, and chemical speciation despite a controlled, soilless environment [4]. This matters because it demonstrates that plants can acquire and allocate mineral nutrients in non-soil systems when those nutrients are presented in accessible forms. The scope of this paper is therefore to explain what soil normally provides in conventional plant growth, and to clarify which of those functions soilless cultivation can substitute directly, which it simplifies, and which it manages differently rather than reproducing in full [4].

II. Background and Scope

The need for a functional account of soil becomes clearer when soilless systems are examined alongside attempts to reintroduce selected soil-like processes. A review of bioponics identifies four broad approaches for producing organic nutrient solutions: tea-type extraction, aerobic microbial degradation, anaerobic digestion, and combined anaerobic-aerobic degradation [5]. These approaches are relevant because they show that once cultivation is separated from soil, nutrient supply no longer arrives as an emergent property of a complex medium. Instead, it must be generated and managed through explicit technical pathways. This distinction helps define the scope of the present paper. The concern here is not detailed soil chemistry or microbial ecology, but the broader question of what soil ordinarily accomplishes for roots, and how those accomplishments are replaced or reformulated when plant growth is moved into a soilless system [5].

Soilless cultivation literature commonly describes the root environment as something that can be deliberately engineered. One recent review characterises soilless cultivation as the artificial regulation of nutrient supply, gas exchange, and microbial communities in order to create favourable crop growth conditions [6]. That description is useful because it

makes the comparison with soil explicit. Soil performs many of these regulatory roles in a coupled and partly self-organising way, whereas soilless systems tend to separate them into controllable variables such as nutrient solution composition, substrate selection, and oxygen availability. The explanatory gap addressed by this paper is therefore not whether plants can grow without soil, but which root-zone services soil bundles together, and how far alternative systems replace those services individually rather than collectively [6].

The complexity of that bundled root-zone environment is particularly evident in the interaction between water and aeration. Research on six pasture soil profiles examined combined soil-water and diffusion-controlled aeration behaviour through depths reaching 117 cm, illustrating that root conditions depend on the co-occurrence of water storage and pore space for gas movement rather than on either property alone [7]. This point sets an important boundary for comparison. A soil can simultaneously retain water, permit drainage, and maintain diffusion pathways for oxygen, but these balances depend on structure and moisture status. Soilless systems may substitute some of these functions with porous media, recirculating solution design, or active oxygen management, yet they do not necessarily recreate the same spatially heterogeneous root-zone dynamics found in soil profiles [7].

III. Core Concepts and Mechanisms

A useful starting point for explaining what soil provides is the concept of plant nutrient supply. Brown, Zhao, and Dobermann argue that a mineral plant nutrient should be understood in relation to whether it is essential or beneficial for growth, development, or harvested-product quality in a given species and environment [8]. Applied to soil, this means the medium is valuable not because it is biologically required in itself, but because it commonly serves as the reservoir and exchange interface through which such elements become available to roots. Soil can store ions on exchange surfaces, release them into soil solution, and moderate the timing of access. Hydroponic systems substitute this function directly by supplying the same mineral elements in prepared nutrient solutions, but they bypass much of the storage and exchange behaviour that soil ordinarily contributes [8].

Hydroponics is commonly defined as a soilless horticultural method in which plants grow in natural or artificial substrates while roots obtain nutrients from a prepared nutrient solution [9]. This definition makes clear that the main soil functions can be partitioned. Anchorage may be provided by an inert substrate, water and mineral nutrients by solution delivery, and root-zone conditions by system design rather than by a natural soil matrix. Mechanistically, this means hydroponics can directly replace some soil services, especially nutrient delivery and water supply, while treating other services as engineering variables. The limitation is that such replacement is selective. A nutrient solution can deliver dissolved ions efficiently, but it does not automatically provide the same chemical buffering, particulate storage, or biologically mediated transformations that occur within a soil body [9].

The broader agricultural significance of this functional perspective is linked to resilience. A recent review defines climate resilience in agriculture as the capacity of food systems to anticipate, absorb, adapt to, and recover from climate-induced shocks while maintaining productivity, resource efficiency, and ecological balance [10]. Within that frame, soil contributes resilience by acting as a multifunctional buffer around roots, while soilless systems contribute resilience by decoupling cultivation from degraded or constrained land. The comparison should therefore not be cast as soil versus hydroponics in absolute terms. Rather, each approach stabilises root function through different mechanisms. Soil relies on intrinsic structural and chemical properties, whereas soilless systems rely on active control and targeted inputs. This paper uses that distinction to explain why some soil functions are substituted directly and others are simplified or externally managed [10].

IV. Evidence Synthesis

Reviews of soilless culture define it broadly as plant growth without soil as the rooting medium, usually with roots contained in a porous substrate or comparable growing medium [11]. This definition helps clarify the first major soil function, physical support. In soil, roots are anchored within a structured matrix that also stores water and provides pore continuity. In soilless systems, these roles can be separated. A porous medium can provide root support and some water-holding capacity, while nutrient solution management handles mineral supply more directly. The evidence therefore supports a functional comparison in which anchorage, moisture retention, and gas movement are seen as root-zone services that can be redistributed across system components rather than as inseparable properties of soil alone [11].

Substrate comparison studies reinforce the point that not all replacements behave alike. Lettuce experiments comparing dried sphagnum moss, wood chips, hemp fibres, and rockwool show that soilless substrates can differ dynamically in their chemical and physical properties, with consequences for plant phenotype [12]. This matters because it demonstrates that even within soilless cultivation, root support media are not merely passive holders of plants. They influence water availability, aeration, and chemical conditions in ways that partly echo soil functions, although usually with lower biological and mineral complexity than field soils. The implication is that hydroponic substitution is not a single model. Some systems use substrates to mimic selected physical functions of soil, while others minimise the substrate role and rely more heavily on direct solution control [12].

A broader synthesis from the soilless production literature suggests that these substitutions become especially relevant where soil quality is poor or water availability is limited. One review frames soilless cultivation as a useful option in severely degraded soils and water-constrained settings, and as a potentially environment-friendly production pathway linked to food security [13]. For the present topic, that evidence does not diminish soil's normal value. Instead, it clarifies the comparison: where soil functions are absent, unreliable,

or difficult to manage, soilless systems can replace selected services through designed root environments. However, they do so by narrowing the problem to controllable variables, not by reproducing every process of a living soil system. That distinction is essential for avoiding the false claim that all hydroponic systems replicate all soil processes [13].

V. Practical Implications and Limitations

From a practical standpoint, hydroponics shows most clearly how some soil functions can be substituted directly. Reviews describe hydroponics as a system in which plants receive a nutrient-rich water solution directly, enabling control of nutrient levels, efficient water use, and cultivation in areas with poor soil quality [14]. This means that soil's roles in nutrient delivery and water supply can be externalised into a managed solution stream. In many cases, anchorage can also be separated out and assigned to a neutral substrate or support structure. The limitation is that direct delivery requires continuous management. Where soil can buffer short-term fluctuations through storage and exchange, hydroponic systems depend more heavily on monitoring and adjustment because the root zone is less buffered by default [14].

Reported production advantages of soilless systems also need careful interpretation. One review states that leafy-vegetable yields are often reported at 200 to 300% above open-field cultivation, while water consumption may be reduced by 80 to 95% [15]. These figures suggest that bypassing some soil functions can deliver strong performance when root conditions are tightly controlled. Yet they do not show that soil is unnecessary in a biological sense, nor that every soil function has been reproduced. Rather, the evidence indicates that some conventional soil services, especially water storage, nutrient access, and local root-zone regulation, can be replaced with more direct and efficient technical control in certain production contexts. Generalisation beyond the reported systems should therefore remain cautious [15].

The same caution applies to broader comparisons between hydroponics and conventional agriculture. Another review reports that hydroponics can achieve significantly higher yields than conventional cultivation, but also notes higher energy consumption [16]. This trade-off is central to understanding what soil normally provides. Soil supplies multiple root-zone services passively, drawing on its structure, exchange surfaces, and resident biological activity. Soilless systems can replace selected services with greater precision, but often at the cost of additional infrastructure, energy, and management effort. A balanced interpretation is therefore that hydroponics does not prove soil irrelevant. It demonstrates that plant growth depends on root-zone functions that can be supplied by different means, with different efficiencies, risks, and operating requirements [16].

VI. Conclusion

Soil normally provides plants with a multifunctional root-zone environment rather than a single isolated input. It anchors roots, stores and distributes water, retains and exchanges nutrients, preserves pore space for gas movement, moderates chemical conditions, and hosts biological activity that can influence nutrient availability and uptake [1], [7]. The evidence considered here supports the central argument that plants do not possess an intrinsic requirement for soil itself. Instead, they require the functions that soil often integrates, and soilless systems succeed when those functions are supplied through nutrient solutions, substrates, and deliberate environmental regulation [4], [6], [9].

The most useful comparison between soil and hydroponics is therefore functional rather than categorical. Some soil functions, especially nutrient supply, water delivery, and physical support, can be substituted directly. Others, including buffering and biologically mediated transformations, are simplified, externally managed, or only partly represented in many soilless systems [11], [13], [14]. Future work is most valuable when it clarifies which root-zone services must be actively engineered in different soilless designs, and which soil functions can be bypassed without compromising plant performance. That framing keeps the comparison scientifically precise and avoids the mistaken assumption that productive plant growth requires soil as a material medium rather than as a provider of functions [16].

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