What Plants Actually Need

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***Abstract*—Higher plants are often discussed as though they require soil, yet the evidence shows that soil is better understood as one possible delivery environment for a set of biological resources and physical conditions. This paper explains what plants actually need at a high scientific level, with particular attention to why soil can be replaced in soilless cultivation. The review scope is deliberately limited to broad growth requirements rather than detailed internal physiology. Across the evidence base, plant performance depends on access to mineral nutrients in plant-available forms, water, suitable root-zone aeration, and a root environment whose physical and chemical properties support uptake and growth. Studies in soil, sand, in vitro media, and soilless systems consistently indicate that nutrient availability, not soil as a substance, is the decisive factor for acquisition and growth response. Soil remains agronomically important because it can buffer water, exchange ions, and host beneficial microbial activity, but these functions can also be provided or regulated by engineered systems. The practical implication is that hydroponic and related systems work when they reproduce the functions that matter to plants rather than the material identity of soil itself. This clarifies both the promise of soilless cultivation and the limits of oversimplified claims about replacing soil.**

I. Introduction

A common misunderstanding in crop production is that plants require soil itself, as though roots consume soil as a material. The evidence reviewed here supports a different interpretation. Soil is agronomically valuable because it often provides a functional package: it can retain water, exchange and buffer ions, and support microbial communities that influence nutrient bioavailability. Soil organic matter is especially important within that package because it is associated with greater cation exchange capacity, improved water retention, and richer microbial biodiversity, all of which can help make nutrients available for uptake [1]. This matters because it shifts the central question from whether plants need soil to whether a growth system can provide the same essential resources and conditions by other means. The implication is that soil replacement is conceptually possible, but only if its useful functions are recognised and reproduced rather than ignored.

Evidence from controlled studies also shows that plant growth responds to nutrient availability across contrasting rooting environments, which weakens the claim that soil is uniquely required. In greenhouse comparisons using sand and natural soils, increasing nutrient availability raised photosynthetic capacity and reduced the carbon cost of nitrogen acquisition, while leaf ci/ca remained unchanged across treatments [2]. The important point for this paper is not the detailed physiology of photosynthesis, but the broader inference that plants respond to the supply conditions of essential resources. Complementary in vitro evidence further shows that species differ in mineral accumulation, net utilisation efficiency, and nutrient recovery even when grown on defined media, indicating that roots acquire plant-available mineral forms from the surrounding solution rather than by ingesting soil itself [3]. Accordingly, this paper argues that plants require resources and suitable conditions, not soil as a substance, and it develops that argument through background, core concepts, evidence synthesis, and practical limits.

II. Background and Scope

Prior work on soilless and related cultivation methods helps define the scope of this argument by showing that the root environment can be assembled deliberately rather than inherited from field soil. For example, bioponic research has classified organic nutrient-solution production into tea-type extraction, aerobic microbial degradation, anaerobic digestion, and combined anaerobic-aerobic degradation [4]. These categories differ in processing route, but they converge on the same principle: plant growth depends on whether nutrients are transformed into forms that can be supplied effectively to roots. This does not mean all systems perform equally well, nor does it imply that any nutrient-rich liquid is adequate. Instead, it shows that the relevant technical problem is functional nutrient delivery. That framing is central to the present paper, which is concerned with what plants need in broad terms, not with the full engineering detail of every cultivation platform.

The broader soilless literature reinforces this functional perspective. Soilless cultivation is described as the artificial regulation of the root environment, including nutrient supply, gas exchange, and microbial communities, in order to create favourable growth conditions [5]. This description is useful because it identifies the broad plant requirements without collapsing them into one material substrate. Plants need a root zone that supplies water and dissolved minerals, permits oxygen exchange, and maintains conditions compatible with growth. Soil may provide these imperfectly and variably, while engineered systems may provide them more directly or more precisely. The gap in many popular explanations is that they jump from the claim that hydroponics works to the claim that soil is irrelevant. The evidence supports a more careful statement: soil is not inherently required, but the functions that support plant growth remain absolutely required and must be managed by alternative means [5].

Root-zone aeration provides a particularly important boundary for this discussion because it shows why a broad resource list must include physical as well as chemical conditions. Work

on pasture soils examined combined soil-water behaviour and diffusion-controlled aeration through profiles extending to 117 cm, highlighting that root performance depends on the co-requirement of water and oxygen availability [6]. This is directly relevant to the present topic. If plants required only nutrients and water, then any saturated environment would suffice, yet poorly aerated root zones commonly constrain performance. The conceptual gap addressed in this paper is therefore not merely whether nutrients can be supplied without soil, but how the necessary conditions for uptake are maintained when soil is absent. That boundary keeps the analysis at the required depth: broad enough to explain why soil can be replaced, but restrained enough to avoid pre-empting detailed treatment of later mechanisms.

III. Core Concepts and Mechanisms

A first core concept is that a plant nutrient is defined by function, not by its presence in soil. Contemporary plant nutrition work proposes that a mineral plant nutrient should include elements that are essential or beneficial for plant growth, development, or harvested-product quality in a given species and environment [7]. This definition is important because it locates plant need in the relationship between the plant and the available element, not in the bulk material through which that element happens to be delivered. In practical terms, plants require mineral nutrition in plant-available forms, typically dissolved species that roots can access from the rhizosphere or an engineered solution. The implication is that the statement "plants need soil" confuses a common carrier with the actual requirement. A limitation, however, is that broad nutrient definitions do not by themselves specify optimal concentrations, interactions, or species-specific balances.

A second core concept is that hydroponic systems work by separating the functions of rooting support and nutrient delivery. Hydroponics is described as a soilless horticultural method in which plants are grown on natural or manufactured substrates while roots extract nutrients from a prepared nutrient solution [8]. This distinction matters because it shows that plants do not require a nutritive soil matrix around roots at all times. They may require physical anchorage, moisture continuity, and an accessible chemical environment, but these can be provided by water culture or by inert and semi-inert media paired with solution delivery. The mechanism relevant here is simple at a conceptual level: if dissolved nutrients, water, and suitable root-zone conditions are available, roots can function without soil. The limitation is that removing soil also removes many passive buffering functions, so system control becomes more consequential [8].

A third core concept concerns why this question matters beyond narrow cultivation technique. Reviews of soilless agricultural systems define climate resilience 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 [9]. Within that frame, understanding what plants actually need clarifies why cultivation can be decoupled from degraded or unavailable soils in some contexts. However, resilience should not be treated as proof that any soilless system is universally superior. The evidence used here supports a conceptual point: because plant needs are resource-based rather than soil-based, cultivation systems can be designed to meet those needs under diverse constraints. What remains uncertain at this level of analysis is which design performs best under particular economic, environmental, or infrastructural conditions [9].

IV. Evidence Synthesis

The evidence base converges on a stable definition of the problem. Soilless plant culture is defined as growing plants without soil as a rooting medium, usually with roots held in a porous substrate or comparable medium [10]. Read together with the nutrient and aeration evidence, this definition implies that soil removal does not abolish plant requirements, it redistributes responsibility for meeting them. Water must still be supplied, mineral nutrients must still be present in available forms, and the root zone must still remain physically suitable for exchange processes. Soil, then, should be interpreted as one historically dominant technology for satisfying these requirements. Its replacement is plausible because the requirements themselves are more general than the substrate. This synthesis directly supports the claim that plants require resources and suitable conditions rather than soil as a substance [7], [10].

Comparative substrate evidence strengthens that conclusion by showing that multiple non-soil materials can support growth, while their differing chemical and physical properties still influence plant phenotype. In greenhouse lettuce production, dried sphagnum moss, wood chips, and hemp fibres were compared with rockwool as soilless substrates [11]. The significance of such comparisons is not that all substitutes are interchangeable, but that roots can function across very different support materials when the root environment remains workable. This helps distinguish broad plant requirements from the internal mechanisms that process them. Plants do not need a specific geological substance called soil, but they do need a support environment whose moisture behaviour, aeration characteristics, and chemical dynamics do not obstruct uptake and growth. The limitation is that substrate choice still matters because alternative media can change the balance of those conditions [11].

The wider review literature places these findings in an agronomic context. Soilless cultivation has been framed as a useful production option where soil degradation is severe and water is limited, with possible environmental advantages and links to food security [12]. That framing is consistent with the functional argument developed here: systems that directly manage nutrient solution and root conditions can sometimes compensate for the absence or poor quality of soil. At the same time, the evidence does not justify an absolutist conclusion that soil is obsolete. Soil remains a powerful multifunctional environment, and in many settings its ecological and agronomic roles are profound [1]. The synthesis therefore supports a balanced answer to the reader question. Plants do not require soil itself, but they do require the resources and conditions

that soil often provides, and those functions must be replaced intentionally when soil is removed.

V. Practical Implications and Limitations

From a practical perspective, hydroponics demonstrates the most direct application of this conceptual distinction. It is described as a soilless system in which plants receive a nutrient-rich water solution directly, allowing control of nutrient levels, efficient water use, and production in areas with poor soil quality [13]. This directness is precisely why hydroponics is a useful example for explaining what plants actually need. The system does not ask roots to mine nutrients from a heterogeneous soil matrix. Instead, it supplies water and dissolved minerals in a managed form, while the grower separately addresses support, aeration, and environmental control. The implication is that successful soilless cultivation depends less on mimicking soil materially and more on reproducing its essential services in controllable ways. A limitation is that greater control also creates greater dependence on correct monitoring and management [13], [14].

Reported performance benefits should also be interpreted through the lens of plant requirements rather than as proof of universal superiority. A recent review reported that soilless systems can deliver leafy-vegetable yields often 200 to 300 percent higher than open-field cultivation while reducing water consumption by 80 to 95 percent [15]. These figures suggest that tightly managed delivery of water and nutrients can align closely with plant demand under appropriate conditions. However, the analytical value of such data in this paper is conceptual rather than promotional. Higher output does not mean plants have fewer needs. It means that their needs may be met more precisely when the root environment is engineered effectively. The limitation is that such reported gains are crop-specific and system-dependent, so they should not be generalised beyond the evidence provided [15].

The main constraint on oversimplified advocacy is that hydroponics may raise output while also increasing other burdens. Reviews note that hydroponics can produce significantly higher yields than conventional agriculture, but often with higher energy consumption [14]. Broader sustainability discussions further observe that human demand already exceeds planetary biocapacity by 56 percent, or about 1.56 times Earth's regenerative capacity, which makes resource efficiency an urgent concern [16]. Together, these points indicate that replacing soil is not equivalent to eliminating trade-offs. The highest-value practical lesson is therefore careful calibration of claims. The evidence supports the proposition that soil can be replaced because plants need resources and suitable conditions, not soil as a substance. It does not support the stronger claim that every soilless system is automatically lower-impact, simpler, or universally preferable [14], [16].

VI. Conclusion

The evidence reviewed in this paper supports a clear answer to the question of what plants actually need. Higher plants require access to water, mineral nutrients in plant-available forms, suitable root-zone aeration, and physical and chemical conditions that allow those resources to be taken up and used effectively [5], [6], [7]. Soil often provides these functions through buffering, exchange, structure, and biological activity, but it is not itself the irreducible requirement [1]. Evidence from sand, in vitro media, substrates, and hydroponic systems shows that roots can function when those essential services are supplied by other means [2], [3], [10], [13]. The promise of soilless cultivation therefore rests on functional replacement, while its limits arise from the need to manage the same requirements explicitly. The most valuable next work, within the boundaries identified here, is continued validation of how different systems maintain nutrient availability, aeration, and root-zone stability under real production constraints, especially where efficiency gains must be weighed against broader resource costs [11], [14], [15].

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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