Future research questions in hydroponics

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***Abstract*—Hydroponic research increasingly concerns coupled biological and engineered processes rather than isolated environmental set points. This paper synthesises unresolved questions that limit reliable interpretation and transfer of hydroponic evidence. Key gaps include root-zone oxygen responses, microbial and hydraulic interactions, crop-specific nutrient and lighting requirements, sensing reliability, and system-level energy and resource trade-offs. The evidence indicates that future progress requires a clear distinction between basic biological questions and engineering validation questions. Biological research must establish causal mechanisms and crop-specific response thresholds, whereas engineering research must test sensor performance, control strategies, durability and generalisability under realistic operating conditions. Comparisons of systems also require transparent reporting and validation across sites, crops and production cycles. Rather than predicting a single technological pathway, this paper frames future hydroponic science as a set of answerable evidence gaps. It argues that reproducible, multi-site and long-duration studies, supported by explicit reporting of biological, hydraulic, nutritional and sensing conditions, are necessary to determine when interventions are effective and when findings can be transferred across environments.**

I. Introduction

Hydroponics enables close management of water, nutrients, gases and light, but this control does not remove biological uncertainty. Plant developmental responses remain partly unresolved even where environmental inputs are specified. In potato, photoperiodic tuberisation involves an unidentified mobile signal, while the proposed causal role of a StPHYF-StPHYB complex remains unproven. Such limits show that controlled cultivation cannot assume that an observed response has a fully established mechanism. A central future research question is therefore how photoperiodic and other long-distance signals interact with crop development under hydroponic conditions. Answering it requires mechanistic experiments that distinguish correlation from causation and test whether conclusions apply across cultivars and production environments [1], [2].

Engineering uncertainty is equally important because hydroponic management depends on measurements that may be incomplete or unreliable. Dissolved-oxygen sensing, for example, is influenced by sensor accuracy, calibration, environmental interference, response time and the need for compensation. A measured value is consequently not identical to the root-zone condition inferred from it. Future research should ask which sensing arrangements remain accurate during changing temperature, nutrient composition and hydraulic operation, and how uncertainty should be propagated into control decisions. This is an engineering validation question, not merely a matter of installing more instruments, because a control strategy cannot be judged independently of the reliability of its inputs [3], [4].

Variation among species, cultivars and environmental conditions also complicates the interpretation of controlled-environment studies. Lighting research reports inconsistent responses when spectral details, calibrated measurements and reporting practices differ, making it difficult to compare apparently similar studies. The future research task is therefore not simply to identify an optimal treatment, but to determine the conditions under which a reported response can be reproduced. This paper examines unresolved questions across root-zone biology, nutrition, lighting, sensing and system design. It argues that progress depends on linking crop-specific mechanism studies with transparent engineering validation and longer-term comparisons across environments [5], [6].

II. Background and Scope

The root zone should be treated as a dynamic biological environment rather than a passive nutrient reservoir. Wider plant nutrition research identifies a lack of universally accepted indicators for soil health, illustrating the broader difficulty of converting complex root environments into simple, transferable measures. Hydroponic research faces an analogous question: which indicators adequately represent root-zone condition when nutrient availability, oxygen status, hydraulic behaviour and microbial activity interact? Future work should establish whether a limited set of measurements can explain crop response, or whether context-specific combinations are necessary. This is a question about evidence quality and operational definition, not a prediction that one monitoring framework will suit every crop or system [7], [8].

Oxygen availability demonstrates why root-zone questions require basic biological research. Plant responses to low oxygen and subsequent re-oxygenation involve unresolved issues in mitochondrial-to-endoplasmic-reticulum signalling, ANAC017 release, gamma-aminobutyric acid function and recovery mechanisms. These gaps matter in hydroponics because roots may experience rapid changes in gas exchange and solution conditions. Research must therefore ask how oxygen stress, recovery and nutrient uptake are connected in particular crops and developmental stages. Controlled threshold experiments can identify response patterns, but they cannot alone establish the signalling mechanisms responsible for them. Mechanistic studies and system trials should be designed as complementary evidence streams [9], [10].

Research on organic nutrient solutions further broadens the scope of uncertainty. Reviews identify outstanding questions concerning physicochemical dynamics, microbiota, mineral losses, health risks and socioeconomic feasibility. These domains should not be collapsed into a single claim of sustainability because each requires different forms of evidence. Chemical balances and microbial dynamics demand biological and analytical studies, whereas feasibility requires comparative evaluation over relevant operating periods. Future research should specify which nutrient transformations and microbial states are being measured, then test whether findings persist across feedstocks, crops and systems. This framing preserves the distinction between an evidence gap and a presumed outcome [11], [12].

III. Core Concepts and Mechanisms

Hydroponic performance arises from interactions among substrate properties, nutrient delivery, root physiology, microbial communities and environmental control. Reviews of soilless cultivation identify unresolved challenges in substrate selection, intelligent control and microbiome engineering. These themes are connected because substrates and hydraulic conditions shape the physical environment in which roots and microorganisms interact, while control systems determine how disturbances are detected and managed. A useful research question is which combinations of substrate, solution management and control logic create stable crop-specific root-zone conditions. The limitation is that apparent system performance may mask distinct underlying mechanisms, so future work needs measurements that separate physical, chemical and biological contributions [13], [14].

Nutrient optimisation requires conceptual clarity before it can be translated into recipes or control targets. Plant nutrition research identifies unresolved questions about operational thresholds for beneficiality and essentiality, together with the need for broader experimental validation. In hydroponics, this means that a concentration associated with a response in one experimental context should not automatically be treated as a universal requirement. Future work should ask how nutrient status, tissue remobilisation, developmental stage and environmental conditions modify the evidence needed to classify an element or treatment as beneficial. Such research is fundamentally biological, although engineering systems can provide the controlled conditions needed to test competing explanations [15], [16].

Lighting presents a comparable interaction problem. Evidence on blue light identifies incomplete species-specific and growth-stage-specific protocols, unresolved photoreceptor crosstalk and limited transferability across production conditions. The central question is not whether blue light has effects, but which spectral combinations, intensities and durations produce reliable responses for a defined crop and developmental stage. Research should report spectra and calibrated exposure conditions in sufficient detail to permit comparison, while testing interactions with other environmental variables rather than treating light as an isolated input. This approach can distinguish genuine crop-specific responses from conclusions that depend on unreported or uncontrolled conditions [17], [18].

IV. Evidence Synthesis

The evidence suggests that research questions must be matched to the scale at which they can be answered. Reviews of medium- and small-scale hydroponics identify unresolved issues in adoption, automation, sustainability and technology transfer. These questions cannot be resolved solely by laboratory demonstrations because operation, skills, maintenance and local conditions affect whether a system can be used consistently. Future research should therefore compare clearly defined configurations across relevant users and environments, while avoiding claims that automation or digital monitoring will inevitably improve outcomes. Engineering prototypes can establish feasibility, but transferability requires evidence from settings that expose practical constraints [19], [20].

Strawberry nutrient film technique systems provide a focused example of interacting uncertainty. Unresolved questions include crop-specific dissolved-oxygen thresholds, the hydraulic effects of root mats and quantitative understanding of Pythium epidemiology. These issues cannot be treated independently because root growth can alter solution flow and oxygen delivery, while altered root-zone conditions may affect disease processes. Future studies should ask how these variables co-vary through a production cycle and whether measurable early indicators predict later crop outcomes. The need is for studies that link root-zone measurements to biological response, rather than relying on generic thresholds derived from other crops or system architectures [21], [22].

This example also clarifies the difference between types of research. Strawberry oxygen sensitivity and Pythium interactions raise basic biological questions about host response and disease development. Hydraulic engineering validation must test how channel geometry, flow conditions and root mats influence local conditions. Threshold experiments are needed to estimate response ranges, epidemiological work is needed to quantify disease patterns, and commercial-cycle studies are needed to test persistence under operational conditions. Treating these as distinct but connected questions prevents an intervention from being judged effective merely because it changes a monitored variable [21], [23].

V. Practical Implications and Limitations

The principal practical implication is that future hydroponic evidence should report the conditions needed to interpret a result. For strawberry systems, unresolved dissolved-oxygen thresholds, root-mat hydraulics and Pythium epidemiology make a single universal recommendation inappropriate. Studies should document crop identity, developmental timing, solution conditions, hydraulic configuration and disease context, then explain which uncertainty each measurement addresses. This supports reproducibility because subsequent investigators can determine whether apparently conflicting findings reflect different biology, different engineering conditions or different

measurement practices. It also limits overgeneralisation from short trials or narrow system configurations [21].

System-level comparisons must address energy-resource trade-offs alongside crop response. Reviews of soilless horticulture identify unresolved questions about context-dependent performance, energy impacts, microbiome management, scalability and economic viability. These questions require comparative designs that make resource inputs, operating assumptions and environmental conditions visible. A system may perform differently when energy demands, crop requirements or local constraints change, so future evaluations should not infer broad superiority from a single context. Long-term studies are particularly important where root-zone stability, maintenance demands and cumulative resource use may differ from short-term performance [24].

Transparent reporting and external validation are necessary because sensing and modelling systems can appear accurate without being generalisable. A hydroponic prototype study identifies the need for larger systems, longer trials, larger datasets and validation across crops and environments. It also notes that plant-wise or time-blocked data splits can reduce leakage risk in predictive models. Future engineering research should test whether models and controllers retain utility outside their development setting, rather than reporting only internal performance. Multi-site validation, explicit calibration records and disclosure of sensor placement, hydraulic conditions and data-splitting methods would make it possible to assess the boundaries of a finding [25].

VI. Conclusion

Future hydroponic science is best understood as a programme of constrained questions rather than a forecast of inevitable technological adoption. The highest-value questions concern how root-zone biology, nutrient status, lighting, hydraulics, sensing and microbial processes interact in particular crops and operating environments. Evidence must distinguish causal biological mechanisms from engineering performance, then test both through transparent and reproducible study designs. Crop-specific oxygen and disease questions, uncertain nutritional thresholds, variable lighting responses and context-dependent system trade-offs show why universal prescriptions remain difficult to justify [9], [15], [17], [21], [24].

Progress will depend on studies that report conditions sufficiently clearly for replication, compare alternatives over appropriate timeframes and validate findings across systems and environments. This includes calibrated sensing, explicit hydraulic and nutrient descriptions, attention to biological context and evaluation beyond laboratory-scale prototypes. Such evidence can identify where an intervention is reliable, where it remains uncertain and which competing explanations deserve further testing. The appropriate endpoint is not a single model hydroponic system, but stronger evidence for making crop- and context-specific decisions [3], [5], [25].

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