Hydroponics for urban and extreme environments

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***Abstract*—Hydroponics is attractive in constrained environments because it replaces dependence on local soil with controlled delivery of water, nutrients, oxygen and other root-zone conditions. This can support cultivation in dense urban areas and places affected by aridity, land degradation or climatic exposure. However, the same control architecture creates dependencies on energy, monitoring, nutrient management, maintenance and replacement inputs. This paper synthesises evidence on hydroponic and related soilless systems in urban and constrained settings, with emphasis on the distinction between operational production, experimental systems and prospective applications. The evidence indicates that recirculating systems can improve control of resource flows but require active management because nutrient composition, sensor accuracy and operating conditions change over time. Reliability becomes particularly consequential where electricity, technical support, communications or resupply are limited. Existing evidence supports documented urban and controlled-environment uses, while evidence for highly isolated and space-related applications is more prospective or research-oriented. Hydroponics should therefore be understood not as a simple substitute for soil, but as an engineered production system whose value in extreme environments depends on resilient operation across biological, physical and technical subsystems.**

I. Introduction

Hydroponics enables crop cultivation without local agricultural soil by supplying water and mineral nutrients directly to plant roots within managed production systems. This characteristic makes it relevant to urban and peri-urban settings, where land is scarce or unsuitable, and to constrained environments where soil quality, water availability or climate limits conventional cultivation. Reviews of medium- and small-scale operations document multiple hydroponic configurations and associated technologies, together with urban case examples that demonstrate the breadth of current application. Yet physical proximity to consumers or freedom from soil does not by itself establish operational resilience. The practical question is whether controlled resource delivery can be maintained when space, skills, energy and replacement supplies are constrained [1], [2].

The promise of recirculation illustrates this distinction. In a nutrient film technique lettuce system, nutrient concentrations did not remain balanced without solution replacement, uptake efficiencies were limited, and nutrient losses occurred despite the use of a recirculating configuration. Maintaining a stable electrical conductivity alone was insufficient because crop demand changed across growth stages. Hydroponics therefore transfers part of the production challenge from field soil management to active management of solution composition, dosing and replacement. In urban, arid, polar or isolated contexts, this transfer can be advantageous only when operators can detect imbalance and respond before root-zone conditions impair production [3], [4].

This paper examines hydroponics for urban and extreme environments as controlled resource-delivery systems rather than as a universally self-sufficient technology. It first defines the scope of evidence, then considers resource-control mechanisms and the operational dependencies that accompany them. The discussion distinguishes established deployments from laboratory systems and prospective concepts, because sensing literature spans benchmark methods, online and industrial monitoring, environmental deployments and future intelligent systems. This distinction is essential when considering isolated and space-related applications, where technical feasibility should not be treated as evidence of routine operational maturity [5], [6].

II. Background and Scope

Root-zone control depends on measurement as well as physical infrastructure. Dissolved oxygen is dynamically affected by conditions including flow, temperature, salinity and pressure, while sensor outputs can also depend on calibration, signal processing and compensation. Consequently, real-time monitoring is valuable in hydroponic systems, but a measured value is only as useful as the reliability of the sensing chain that produces it. In constrained environments, calibration materials, skilled intervention and replacement instruments may be less available. The relevant design problem is therefore not simply whether a variable can be sensed, but whether sensing remains accurate and actionable through changing operating conditions [5], [7].

Operational experience with nutrient film technique systems provides an important counterweight to purely conceptual claims. Historical commercial controlled-environment strawberry production in European greenhouse systems demonstrates that hydroponic production can support long-cycle crops under managed conditions. At the same time, reviews of strawberry NFT systems separate this commercial history from mechanistic experiments concerning dissolved oxygen and root disease, and from proposed future systems research. This evidence supports hydroponics as an operational production approach, but it does not justify assuming that every controlled-environment configuration has equivalent reliability, crop suitability or maintenance requirements [8], [9].

The scope extends across urban, peri-urban, arid, degraded and climate-sensitive environments, where hydroponic, aeroponic and vertical-farming approaches are discussed as forms of soilless horticulture. These contexts share a need to reduce

reliance on productive local soil, but they do not share identical constraints. Dense cities may prioritise space and environmental control, while arid or isolated settings may be more exposed to water balance, input availability and equipment failure. Evidence for urban and constrained terrestrial systems is stronger than evidence for fully isolated or space-related routine production. The analysis therefore treats prospective applications cautiously and focuses on the conditions required for controlled systems to function reliably [10].

III. Core Concepts and Mechanisms

Hydroponic systems are attractive because they make the root zone an engineered environment. Water, dissolved nutrients, oxygen availability and flow can be managed independently of local soil characteristics, allowing production on non-arable land and within protected structures. However, this control introduces coupled dependencies. Energy is required for pumping, environmental conditioning and, where used, lighting; nutrient and water balances require monitoring and adjustment; and equipment, disease and maintenance problems can interrupt production. Reviews of soilless agriculture identify high setup and energy requirements, technical expertise, unreliable electricity, maintenance burdens and equipment failure as important constraints. These dependencies become more consequential where external support or resupply is limited [10].

Hydroponics is one member of a broader family of soilless approaches that includes aquaponics and bioponics. Comparative reviews show that these systems differ in how nutrients are supplied and managed, but each depends on maintaining conditions within acceptable operating ranges. Precision-oriented approaches can improve observability and control, yet they also add sensors, data pathways and actuators that require integration and upkeep. The appropriate system choice therefore cannot be reduced to a generic claim of resource efficiency. It must account for the availability of inputs, labour, technical capability and tolerance for interruptions in the specific production environment [11].

Reliability is a biological as well as an engineering concern. Sensor failure or recalibration needs can obscure developing root-zone problems, while pathogen risks and dependence on material inputs can disrupt production even when the physical growing structure remains intact. In locations with limited resupply, redundancy and serviceability become central design considerations because a failed pump, sensor or dosing component can affect the entire crop environment. Reviews identify these operational challenges alongside energy and capital requirements, indicating that controlled production offers no automatic insulation from resource constraints. Rather, it concentrates key risks into a smaller set of interdependent subsystems that must be managed consistently [11].

IV. Evidence Synthesis

The evidence base supports a graduated view of technological maturity. Measurement research includes experimental in-situ sensing, operational remote sensing and monitoring applications, and prospective innovations such as miniaturised spectrometer-based systems. These categories should not be collapsed into a single claim of readiness. A sensor may perform well in an experiment while still requiring validation for durability, calibration stability and integration with crop management. For urban and extreme environments, the useful question is whether monitoring improves decisions under actual operational conditions, rather than whether a measurement method is technically possible in principle [12].

Laboratory hydroponic prototypes provide useful evidence about control architectures but have bounded generalisability. One integrated hydroponic system addressed sensor failure risks and considered power and cloud continuity by incorporating local edge control intended to preserve operation when cloud support was unavailable. This design directly addresses a plausible vulnerability in distributed controlled agriculture: remote services may not be continuously reachable. Nevertheless, the reported system remained limited in scale and validation setting. Local control can reduce dependence on external connectivity, but it does not remove the need for reliable power, calibrated sensors, maintainable actuators and operator capacity [13].

The same study distinguished laboratory-scale prototype development and closed-loop validation from future larger-scale, longer-duration and externally validated use. This distinction is particularly important for claims about isolated, polar or space-related production. Controlled experiments can establish that a component or control strategy functions under defined conditions, whereas operational deployment requires continued performance across maintenance cycles, disturbances and supply limitations. Evidence should therefore be interpreted according to the maturity of the system being described. Demonstrated closed-loop operation is meaningful evidence, but it is not equivalent to proof of resilient, long-duration production in highly constrained environments [13].

V. Practical Implications and Limitations

Routine hydroponic management can require considerable operational support. A hydroponic greenhouse system incorporating automatic calibration, cleaning, pH correction, wireless monitoring and acid dosing illustrates how control depends on both sensing and physical intervention. Network limitations, chemical operating conditions and maintenance workload remain relevant even when parts of the process are automated. Such systems can reduce manual burden for specific tasks, but they also create requirements for calibration fluids, pumps, communications and maintenance procedures. In settings with limited local resources, maintainability and recovery from component faults should be considered alongside normal-state control performance [14].

Current evidence also cautions against treating digital control as a single mature category. Reviews of closed soilless horticulture distinguish commercial observations and interventions from controlled experiments, simulations, proof-of-concept systems and speculative digital-control applications. This differentiation matters because the evidence required for

a commercial facility differs from that required for a model or prototype. Urban production may be able to draw on established services and supply networks, whereas isolated facilities may face longer repair times and fewer fallback options. Claims about resilience should consequently identify whether they concern observed operation, experimental performance or future design potential [15].

Resource recovery and treatment concepts require similar caution. Reviews of hydroponic production discuss current practices, reported experimental systems, early demonstrations, proposed bioelectrochemical configurations and possible scale-up pathways. These strands of evidence indicate active development, but they do not establish that every proposed treatment or recycling approach is ready for routine use in constrained environments. The highest-value validation need is integrated, long-duration testing that examines nutrient balance, crop health, maintenance demand and fault recovery together. Such testing would better reveal whether a system can sustain controlled production when replacement materials and technical intervention are delayed [16].

VI. Conclusion

Hydroponics is attractive in urban and extreme environments because it can decouple root-zone production from local soil and enable deliberate control of water and nutrient delivery. The evidence also shows that this advantage is conditional. Recirculating nutrient solutions require active composition management, while dependable production depends on energy, instrumentation, maintenance, disease control and access to inputs. Urban and controlled-environment deployments demonstrate meaningful operational relevance, but highly isolated and space-related applications remain more strongly represented by research, prototypes and prospective discussions than by evidence of routine long-duration deployment [3], [8], [13].

The central implication is that hydroponic resilience should be evaluated as system resilience rather than as a property of soil-free cultivation alone. Future progress requires validation that joins root-zone management, sensing reliability, local control, maintenance and resource recovery under realistic constraints. Evidence from soilless agriculture supports this integrated perspective because high energy and capital requirements, sensor recalibration, pathogen risks and input dependence can all limit otherwise promising controlled systems. Clear separation of operational deployments from experimental and speculative concepts will improve decisions about where hydroponics can reliably contribute to constrained-environment food production [11], [15].

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