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A REVIEW OF SMALL-SCALE IOT-ENABLED HYDROPONIC SYSTEMS: SENSORS, NUTRIENT MANAGEMENT, LIGHTING, AND PRACTICAL DESIGN CONSIDERATIONS

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ABSTRACT

Hydroponic cultivation—growing plants in nutrient-rich aqueous solutions—has emerged as a promising approach for intensive, space-efficient agriculture in urban and controlled-environment applications. Recent literature emphasizes three converging themes for small-scale systems: (1) precise nutrient management (EC/TDS and pH control), (2) environmental sensing and IoT-based remote monitoring, and (3) adaptive LED lighting and photoperiod control. This review surveys the state-of-the-art (2022–2025) in hydroponic system designs, sensing technologies, control architectures (microcontroller-to-cloud), nutrient dosing strategies, and lighting management. We identify common limitations in low-cost implementations—sensor drift and calibration, fail-safe handling of pumps/reservoirs, and energy consumption of lighting—and summarize best-practice recommendations for a robust pilot system. The review maps the literature findings to a practical design roadmap (components, sensors, control logic) suitable for educational demonstrations and prototyping. Key research gaps and future directions—including improved low-cost ion sensing, adaptive control algorithms, and pathogen mitigation strategies—are highlighted to inform both academic and applied projects in technical education.

INDEX TERMS: Hydroponics, IoT, ESP32, EC/TDS, pH control, LED grow lights, Nutrient Dosing, Sensors, Vertical Farming, Technical Education.

I. INTRODUCTION

Hydroponic systems offer controlled growth environments that can increase yield while minimizing land and water use compared with soil-based agriculture. Over the last three years (2022–2025), many reviews and scoping studies have systematized knowledge about hydroponic architectures (NFT, DWC, ebb-and-flow, aeroponics), sensing/actuation components, nutrient management protocols, LED lighting strategies, and IoT-enabled monitoring platforms suitable for small- to medium-scale applications [1] [6]. For educational prototypes and small-scale pilot systems, research focuses on low-cost sensing, microcontroller-based control (Arduino/ESP32), and cloud dashboards for telemetry and alerts [7] [10]. This review synthesizes contemporary findings (2022–2025), organizes the literature around core technical parameters (environment, nutrient solution, operational telemetry, and hardware), and produces a design-oriented literature synthesis to support prototyping and implementation in technical education contexts.

II. Classification of Hydroponic Systems and Application Context

Hydroponic systems are commonly classified by the method of nutrient delivery: Nutrient Film Technique (NFT), Deep Water Culture (DWC), ebb-and-flow/ flood-and-drain, drip systems, and aeroponics. Each class has different requirements for pump reliability, oxygenation, nutrient monitoring, and reservoir design [3] [5]. For small educational pilots, NFT and DWC/ebb-and-flow layouts are frequently preferred due to simplicity, reduced mechanical complexity, and well-documented parameter ranges in the literature [1] [11]. Vertical / stacked NFT modules are common for space-limited indoor lab projects (urban agriculture), but they increase the importance of uniform flow distribution and monitoring at multiple points [11] [12].

III. Environmental Parameters: What to Measure and Why

The literature converges on a short set of environmental parameters that strongly influence growth and should be monitored in any small-scale automated hydroponic system:

- **Air temperature & humidity:** Affects transpiration and disease risk; tight control improves plant health. Recommended sensor cadence: 1–15 min depending on system dynamics. [4] [6].
- **Light intensity & photoperiod (lux/PPFD and hours):** Critical for photosynthesis and morphological traits; LED spectral composition (red:blue ratios) and photoperiod scheduling

are active research areas. Use PAR/PPFD-capable sensors where possible for precision, but low-cost lux sensors are acceptable for pilot studies [9] [13].

- **Reservoir water temperature:** Influences dissolved oxygen and nutrient availability; recommended to maintain within crop-specific bounds (commonly 18–24 °C for many leafy greens) [5].
- **CO₂ (optional):** Not required for small pilots but relevant for controlled-environment scaling.

These parameters guide control actions (LED schedule adjustments, heater/chiller controls, ventilation) and should be integrated into the system telemetry [4] [9].

IV. Nutrient Solution Monitoring and Management

Precise nutrient control is a major advantage of hydroponics but also a technical challenge. The core measurable variables and their relevance:

- **Electrical Conductivity (EC) / Total Dissolved Solids (TDS):** Proxy for ionic concentration — used to track nutrient strength. EC-based dosing algorithms (setpoint + automated dosing to compensate for uptake and dilution) are standard in automated solutions
- **pH monitoring & control:** Many nutrients' bioavailability is pH-dependent. Low-cost pH probes are widely used but require frequent calibration and regular maintenance to avoid drift. The literature documents both on-line dosing approaches and periodic manual calibration strategies to mitigate sensor drift [6] [14].
- **Water level & flow sensors:** Protect against pump dry-run and enable reservoir management—critical fail-safe metrics for small systems [7] [15].
- **Dissolved oxygen (DO):** Helpful in aquaponic and certain DWC applications but optional for basic NFT/ebb-and-flow setups.

Recent reviews propose closed-loop control strategies combining periodic EC/pH sampling with rule-based or PID dosing actuators; machine-learning-based adaptive dosing is proposed in advanced settings but is less common in low-cost systems due to the need for larger datasets [8] [16]. Practical recommendations stress redundancy (two-point level sensing), regular scheduled calibration, and conservative fail-safe thresholds for dosing and pump operation [6] [14] [15].

V. Sensors, Calibration, and Practical Limitations

Low-cost sensors are accessible for prototyping but introduce challenges that are valuable learning points in technical education:

- **pH sensors:** prone to drift—require frequent two-point calibration (pH 4 and 7 buffers) and, where possible, probe replacement schedules. Literature suggests off-line calibration logs and in-software reminders to avoid long-term biased control loops [6] [14].
- **EC/TDS probes:** generally robust but influenced by water temperature; temperature compensation is recommended (most modern EC sensors include built-in temperature compensation or require software compensation) [6].
- **Light sensors:** lux vs. PAR/PPFD trade-offs — lux sensors are cheaper but less directly correlated to photosynthetic photon flux, especially when LED spectra vary; if the budget allows, a PAR sensor or calibrated lux-to-PPFD conversion for the chosen LED spectrum improves control fidelity [9] [13].
- Flow and level sensors: inexpensive float switches and ultrasonic level sensors are practical options for reservoir monitoring; flow sensors help detect pump blockages or airlocks [7] [15].

The reviews stress documenting sensor specifications and calibration procedures to ensure experimental rigor and educational value [1] [6].

VI. IoT Architectures and Microcontroller Choices

The literature shows a strong trend to ESP32-based controllers for small hydroponic pilots due to integrated Wi-Fi, low cost, and extensive community support, making it an ideal platform for teaching IoT concepts [7] [10]. Typical architecture patterns:

1. **Edge-only:** ESP32 logs locally (SD card) and controls actuators directly—simple and robust for offline operation.
2. **Edge + Cloud:** ESP32 publishes telemetry to cloud services (HTTP/MQTT) for dashboards, alerts, and long-term analytics. Requires handling intermittent connectivity and securely storing credentials [7] [10].
3. **Edge + Local Server:** ESP32 communicates with a local Raspberry Pi server that provides dashboards and stores historical data—preferred where privacy or limited bandwidth is a concern.

Relevant design advice includes using secure MQTT with authentication for cloud telemetry, implementing watchdog timers and hardware-level fail-safes for pumps and relays, and logging critical events locally to support debugging after outages [7], [10] [15].

VII. Lighting: LED Design, Spectra, and Photoperiod Control

LEDs are the standard for indoor hydroponics because of efficiency and spectral control.

Recent reviews summarize:

- Use combined red and blue spectra (with variable ratios) to tune morphology; supplemental white or far-red may be used for specific crops.
- Photoperiod strategies (e.g., 16:8 for many leafy greens) affect growth rate and leaf development—automated scheduling via microcontroller timers (RTC or NTP) is common [9] [13].
- Energy efficiency vs. spectral quality trade-offs: the literature advises measuring PPFD at canopy level and controlling dimming through PWM channels on LED drivers to balance growth and electricity consumption [9] [12].

For educational systems, a single multi-channel LED with PWM dimming controlled via a microcontroller like the ESP32 can effectively demonstrate spectral and photoperiod effects without excessive complexity [9].

VIII. System Reliability, Fail-safes, and Hygiene

Multiple reviews emphasize the importance of fail-safe design for pumps, reservoirs, and nutrient reservoirs to avoid crop loss, a critical consideration for successful long-term projects:

- **Pump monitoring:** Current sensing or flow sensing to detect pump failure; automatic shutdown and alerts if anomalous behaviour detected [15].
- **Reservoir contamination mitigation:** Use UV sterilization, periodic reservoir flushing, and temperature control; maintain hygiene protocols to reduce biofilm and pathogen risk [4] [6].
- **Power-failure handling:** Use RTC and state-saving to resume safe defaults after outages; combine with battery backup for short interruptions in critical systems.

Documenting these safety and hygiene practices demonstrates awareness of operational risks and is a key outcome for technical training [1] [6] [15].

IX. Challenges, Open Questions & Future Directions

Despite progress, the literature highlights research gaps that are especially relevant for educational projects and small-scale pilots:

- **Low-cost ion-specific sensing:** Accurate nitrate, potassium, and calcium sensing remains expensive; research into low-cost selective sensors or reliable proxies is ongoing [6], [16]. This presents an open challenge for student innovation.
- **Sensor drift & long-term calibration:** Robust calibration routines and low-effort maintenance protocols are critical for long-duration deployments and are a key area for developing best practices.
- **Adaptive control algorithms:** ML-based adaptive dosing shows promise but requires datasets; small pilots can explore semi-supervised strategies and transfer learning from published nutrient uptake curves [8] [16].
- **Pathogen detection & biosecurity for recirculating systems:** Rapid, low-cost detection remains a challenge and an active research area [4].

These topics suggest ample opportunities for incremental research contributions and advanced student projects, particularly in comparing control algorithms or developing novel calibration techniques.

X. CONCLUSION

This review synthesized recent (2022–2025) literature on hydroponic system design, focusing on core technical parameters (environmental, nutrient, and operational telemetry) and low-cost IoT-enabled control solutions. We identified practical choices—sensor selection and calibration, conservative dosing strategies, LED control, and fail-safe architectures—that provide a clear roadmap for prototyping and implementation. The literature indicates ample opportunity for contributions in low-cost sensing, adaptive dosing algorithms, and system robustness, making it a fertile ground for projects in technical education. The next logical step is to translate this design roadmap into detailed implementation—including circuit diagrams, firmware architecture, and data visualization—enabling the experimental evaluation of system performance and its effectiveness as an educational tool.

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