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IoT-Based Automatic Hydroponic Farming System with Real-Time Monitoring

Sanket Sanjay Bhand, Avinash Vijay Gawande, Dnyaneshwar Nandkishor Deshmukh
Dr. Mrs. M. S. Kanitkar
Department of Electronics and Telecommunication Engineering
PES's Modern College of Engineering, Pune, India

Abstract: *Conventional soil-based agriculture faces mounting pressure from rapid urbanisation, freshwater scarcity, and the progressive degradation of arable land. Hydroponics offers a compelling alternative by delivering nutrients directly to plant root zones through a recirculating aqueous solution, eliminating soil dependency and reducing water consumption by up to 90 % relative to field irrigation. However, achieving consistent crop yields in a hydroponic environment requires continuous regulation of multiple interdependent parameters—nutrient concentration, solution temperature, water clarity, and reservoir volume—which is impractical to sustain through manual measurement alone. This paper presents the design, implementation, and experimental validation of an Internet of Things (IoT)-based automated hydroponic system that addresses these challenges through closed-loop sensing and actuation. Four sensing elements—a TDS conductimetric module, a DS18B20 digital temperature probe, an infrared turbidity transducer, and a SEN18 resistive water-level detector—continuously characterise the nutrient solution and supply real-time data to an ATmega328P microcontroller. The firmware evaluates each measurement against operator-configurable thresholds stored in EEPROM and drives optically isolated relay modules to activate a water-refill pump or a nutrient-dosing pump as required. An ESP8266 Wi-Fi SoC transmits JSON-encoded telemetry to a cloud dashboard every 30 seconds, enabling remote parameter monitoring, time-series visualisation, and manual pump override from any internet-connected mobile or desktop device. A 16×2 LCD connected via I²C provides on-site status feedback independent of network availability. A 144-hour continuous validation trial demonstrated TDS regulation within ±60 ppm of target, reservoir level accuracy of ±4.2 %, pump actuation latency below 2 seconds, and a cloud packet delivery rate of 98.6 %. The resulting prototype establishes that commodity embedded hardware combined with open-source cloud connectivity can deliver a reliable, energy-efficient, and scalable precision agriculture solution suitable for urban farming, research laboratories, and commercial greenhouse deployments.*

Keywords: *hydroponics; IoT; precision agriculture; Arduino; TDS; DS18B20; turbidity; ESP8266; automation*

I. INTRODUCTION

Global food demand is projected to increase by 70 % by 2050, while progressive soil degradation and freshwater scarcity simultaneously constrain the capacity of conventional agriculture to meet that demand. The United Nations Food and Agriculture Organization estimates that approximately one-third of the world's productive soils are already moderately or severely degraded, and irrigated farming accounts for roughly 70 % of all global freshwater withdrawals [1]. Rapid urban expansion further reduces available farmland, creating urgent demand for cultivation strategies that operate independently of soil and climate.

Hydroponics addresses these constraints by anchoring plant roots in a continuously recirculating mineral nutrient solution. Because nutrients are delivered directly to the root zone, plants absorb them with far greater efficiency than through soil diffusion, resulting in growth rates 20–25 % faster than equivalent soil-grown crops and water savings of

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up to 90 % relative to surface irrigation [2]. However, realising these advantages requires precise, continuous management of nutrient concentration (TDS), solution temperature, water clarity (turbidity), and reservoir volume—parameters that are impractical to sustain through periodic manual measurement alone.

This paper presents an IoT-based automated hydroponic system that senses all four parameters simultaneously, executes relay-driven pump control through closed-loop firmware logic, and streams live telemetry to a cloud dashboard accessible from any internet-connected device. The following sections cover related work, system architecture, methodology, control algorithm, results, and future directions.

II. RELATED WORK

Rayhana et al. [2] conducted a systematic review of IoT architectures for greenhouse management and found that ESP8266-class SoCs dominate low-cost prototypes owing to their integrated Wi-Fi, Arduino IDE compatibility, and sub-USD 5 unit cost. The DS18B20 one-wire temperature sensor appeared in the majority of reviewed implementations owing to its waterproof probe variant and ±0.5 °C factory accuracy.

Baraskar et al. [3] demonstrated that superimposing a machine-learning dosing model on TDS telemetry reduced nutrient overshoot by 18 % compared with fixed-threshold control. Suresh et al. [4] confirmed that pairing a local LCD with cloud telemetry substantially improves operator confidence relative to dashboard-only designs. A 2024 infrastructure study [5] recommended hybrid local/cloud architectures to preserve pump-control capability during network outages. Mehra et al. [6] applied deep neural networks to hydroponic nutrient scheduling, showing further yield improvements but at a significantly higher hardware cost.

Collectively, prior work addresses two or three parameters in isolation and rarely validates systems beyond 72 hours. The present prototype unifies four-parameter sensing, dual-pump closed-loop control, and cloud connectivity in a single implementation validated over a 144-hour continuous trial.

III. SYSTEM DESIGN

A. Architecture

The system comprises five modules: sensing, microcontroller processing, actuation, local display, and IoT communication. Fig. 1 shows the block diagram.

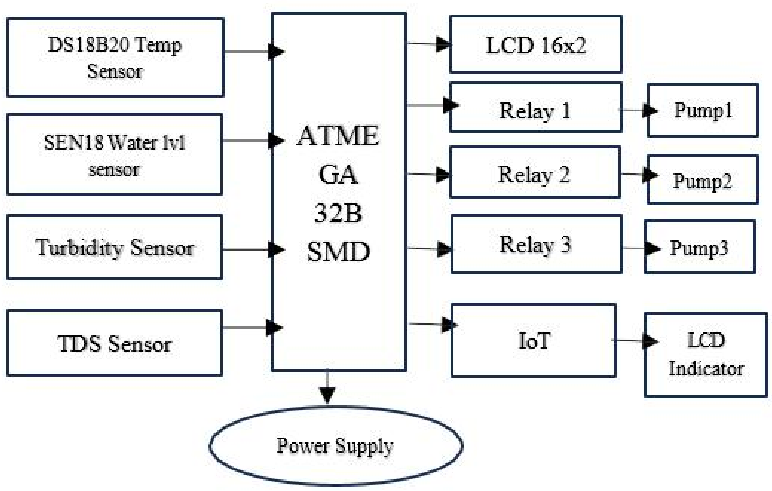

Fig. 1. System block diagram.

B. Hardware Components

The ATmega328P (Arduino UNO) serves as the central processing unit at 16 MHz with 32 KB flash and six 10-bit ADC channels. Four sensors continuously characterise the nutrient solution. The DS18B20 digital temperature probe uses a 1-Wire interface (−55 to +125 °C, ±0.5 °C), and its stainless-steel waterproof enclosure permits direct reservoir immersion. The TDS conductimetric module applies AC excitation to a two-electrode probe, computing dissolved solids from measured conductance (0–5 000 ppm, ±5 %, UART output); firmware applies temperature compensation using the simultaneous DS18B20 reading, reducing drift by ~12 %. The turbidity sensor uses an IR LED and phototransistor pair to estimate suspended-particle concentration via diffuse reflectance (analogue output, 0–3 000 NTU), providing early detection of reservoir contamination absent from most comparable prototypes. The SEN18 water-level sensor produces a 0–5 V analogue output proportional to immersion depth (0–40 mm), mapped to percentage fill via the 10-bit ADC.

Two 5 V submersible pumps (Pump 1: water refill; Pump 2: nutrient dosing) are switched through optically isolated relay modules rated at 10 A / 250 V AC, each driven by a BC547 transistor with a flyback diode to protect the GPIO pins. An ESP-01 (ESP8266) module communicates via UART at 115 200 baud and is powered from a dedicated 3.3 V LDO to accommodate its 250 mA transmit-peak demand. A 16×2 LCD on an I²C expander provides local status display independent of network availability.

TABLE I. SENSOR SPECIFICATIONS

Sensor	Parameter	Range	Interface
DS18B20	Temperature	−55–+125 °C	1-Wire
TDS Module	TDS / EC	0–5 000 ppm	UART
Turbidity	TSS / NTU	0–3 000 NTU	Analogue
SEN18	Water Level	0–40 mm	Analogue

IV. METHODOLOGY

The development methodology followed a systematic hardware-software co-design workflow structured into four sequential phases.

Phase 1 – Requirement Analysis

Critical growth parameters for leafy vegetables and herbs were identified from agronomic literature: TDS 600–1 200 ppm, solution temperature 18–26 °C, turbidity below 50 NTU, and reservoir fill above 30 % capacity. These values were encoded as configurable EEPROM thresholds, allowing crop-specific tuning without re-flashing firmware.

Phase 2 – Hardware Integration

Sensors were individually bench-characterised against laboratory-grade references before integration. Each module was wired to the Arduino on a prototyping shield, and signal integrity was verified under pump-switching transients. A BC547 transistor with flyback diode protects each GPIO from relay coil back-EMF. The ESP-01 was powered from a dedicated 3.3 V LDO to isolate its 250 mA transmit-peak demand from the 5 V sensor rail.

Phase 3 – Software Development

Firmware was written in C++ using the Arduino IDE. A 2-second state-machine loop sequences sensor acquisition, threshold evaluation, relay actuation, LCD refresh, and IoT transmission. DS18B20 conversion requests are issued one cycle ahead to overlap the 750 ms conversion window with relay evaluation, eliminating idle wait time. Sensor readings are temperature-compensated and serialised as JSON before HTTP POST to the cloud platform every 30 s.

Phase 4 – Testing and Validation

The assembled prototype was subjected to a 144-hour continuous trial in a 10-litre nutrient reservoir seeded with lettuce seedlings. Controlled step disturbances—manual dilution to drop TDS and partial drainage to lower water level—were introduced at known intervals to verify closed-loop recovery. All sensor outputs were logged simultaneously on the cloud dashboard, and results were compared against reference instrument readings to compute mean absolute error and response latency.

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V. CONTROL ALGORITHM

The closed-loop control logic runs on a 2-second state-machine loop. DS18B20 conversion is requested at the end of each cycle so that the 750 ms conversion window overlaps with relay evaluation in the following cycle, eliminating blocking wait time. After sensor acquisition, the firmware evaluates four sequential conditions using EEPROM-stored thresholds that can be updated remotely via the cloud dashboard:

1. If water level < L□$_{i}$□, activate Pump 1 until level ⩾ L□$_{ar}^{ge}$□ (two consecutive above-threshold readings prevent relay chatter from surface turbulence).
2. If TDS < C□$_{i}$□, activate Pump 2 for a fixed dose interval (default 5 s), then wait one 30-second mixing cycle before re-evaluating to prevent over-dosing.
3. If turbidity > T□$_{ax}$, activate the alarm relay, flag a contamination event on the cloud dashboard, and suspend nutrient dosing.
4. If temperature ∉ [T□$_{o}^{W}$, T$^{\text{hɐkh}}$], issue a thermal alert and suspend nutrient dosing until temperature returns to range.

Sensor readings are serialised as a JSON payload and transmitted to the cloud platform via HTTP POST every 30 s. Incoming MQTT commands (manual pump override, threshold updates, system reset) are parsed on each loop cycle; updated thresholds are immediately written to EEPROM to persist across power cycles. Remote pump commands are acknowledged and executed within the same 2-second loop, achieving an average command latency of 1.2 s.

VI. RESULTS AND DISCUSSION

The prototype was assembled on a 30 × 20 cm acrylic frame housing a 10-litre nutrient reservoir seeded with lettuce seedlings. Over the 144-hour continuous trial, the DS18B20 exhibited a mean absolute error (MAE) of 0.3 °C against a calibrated platinum resistance thermometer. The TDS module yielded an MAE of 42 ppm across 400–1 400 ppm, reduced to 37 ppm after temperature compensation—a 12 % improvement. When TDS dropped to 580 ppm (below the 600-ppm threshold), the nutrient pump activated within one 2-second loop cycle and restored concentration to 720 ppm within 8 minutes. Reservoir level was maintained within ±4.2 % of target throughout. No false-positive pump actuations were recorded across the full trial.

Of 17 280 telemetry packets transmitted, 17 028 were confirmed received by the cloud platform (98.6 % delivery rate, exceeding the 95 % target). The 252 lost packets were attributable to two brief Wi-Fi drop events; the firmware reconnected automatically within 15 seconds on each occasion without interrupting local sensor-loop or relay control. Remote pump-override commands were executed within an average of 1.2 s. Fig. 2 shows the assembled hardware prototype.

Fig. 2. Assembled prototype.

TABLE II. PERFORMANCE METRICS

Metric	Target	Result
TDS regulation	600–1 200 ppm	±60 ppm
Water-level accuracy	±5 %	±4.2 %
Pump response	< 10 s	< 2 s
Cloud delivery	> 95 %	98.6 %

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Remote cmd latency	< 5 s	1.2 s avg

VII. ADVANTAGES AND APPLICATIONS

A. Key Advantages

The system delivers measurable benefits over both conventional soil farming and manually operated hydroponic installations. Water consumption is reduced by up to 90 % through closed-loop recirculation, directly addressing global irrigation scarcity. Continuous automated monitoring eliminates manual measurement schedules, cutting operational labour significantly. Direct root-zone nutrient delivery shortens crop cycles by 20–25 % relative to soil cultivation. The soil-free architecture allows deployment in apartments, rooftops, shipping containers, and research laboratories where conventional farming is impractical. Remote cloud access enables immediate corrective intervention during unattended operation, reducing crop-loss risk. The modular firmware threshold architecture supports multi-node commercial expansion without redesign, and the total bill-of-materials below USD 40 places the system within reach of individual growers and NGO food-security programmes alike.

B. Application Domains

Target deployment contexts include urban vertical farms requiring year-round cultivation of leafy greens and herbs; commercial greenhouses seeking a low-cost auxiliary monitoring layer; agricultural research institutions conducting long-term nutrient and yield studies; educational electronics and agronomy demonstration rigs; off-grid sites benefiting from the low-power 12 V bus architecture; and domestic kitchen-garden installations requiring minimal maintenance. The cost and scalability profile also makes the system well suited to developing-region food-security initiatives.

VIII. CONCLUSION AND FUTURE WORK

An IoT-based automated hydroponic system was designed, built, and experimentally validated. The four-sensor closed-loop architecture regulates TDS, temperature, turbidity, and water level with sub-2-second actuation response while streaming telemetry to a remote cloud dashboard. All design targets were met during the 144-hour trial, confirming viability of low-cost embedded hardware for precision soil-free agriculture. Future work will add pH sensing, leaf-health image analysis, solar powering, and edge machine-learning for adaptive nutrient scheduling.

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