# Project Report

Household Smart Hydroponic Control Core System: Development and Application

Region: Suzhou, Jiangsu Province, China
School: Jiangsu Suzhou No. 10 High School
Authors: Wang Ziping, Zhu Zhengqiang
Advisors: Zhang Yin, Qian Xiaomin

(This is a condensed English translation of the original Chinese report, prepared for a general audience. The full original-language report is available on request.)

## Abstract

As a key factor for plant growth, water easily causes vegetables to suffer from pesticide residues and excessive heavy metal content in traditional soil cultivation. Hydroponic technology, relying on precise water supply, has clear advantages in water efficiency and safety, offering a high-quality solution for growing healthy vegetables at home. This project uses an STM32F1-series ARM microcontroller as the control core, integrating temperature, humidity, and light sensors with actuators such as fans and water pumps to build a household intelligent hydroponic system. Test results show that the system reliably supports vegetable growth under the constraints of a home environment while significantly conserving water. It is practical and extensible, and can also serve as a plant-cultivation verification platform and an innovative STEM teaching aid for secondary school students.

**Keywords:** Intelligent Control, Embedded Systems, Hydroponics

## 1. Introduction

Water is the foundation of agrarian civilization. Chinese agricultural history has always carried a deep awareness of coexisting with, conserving, and making rational use of water resources — managing water well to support agriculture has long been central to sustaining that civilization.

China, however, is not naturally well-endowed with water: per-capita water resources are only about 28% of the global average, and both scarcity and uneven distribution remain key bottlenecks to agricultural modernization. Finding ways to make every drop of water count is an important challenge for high-quality agricultural development in this new era.

Smart hydroponic technology offers an effective path forward. By using water as the primary growing medium, replacing soil with precisely dosed nutrient solution, and relying on a closed-loop water cycle for efficient reuse, hydroponics can push water-use efficiency above 90%, with water savings of 70–96% compared to traditional cultivation. This "water instead of soil, closed-loop reuse" model not only addresses water scarcity but reshapes the relationship between agricultural production and water resources.

At the same time, urban spaces hold significant untapped potential for efficient water use: the average balcony area per urban resident in China is roughly 1.5 square meters, and if this idle space were brought into a hydroponic growing system, it could theoretically create the equivalent of over 100,000 hectares of "invisible farmland." The household smart hydroponic system in this project was developed with exactly this potential in mind — built around "extreme water efficiency, intelligent circulation" to form a micro-ecosystem that maximizes the use of water and nutrients, while doubling as an engaging teaching tool for water conservation and hands-on labor education for younger students.

## 2. Research Methods

### 2.1 Background Research

Using "soilless cultivation" and "parameter control" as search terms, we reviewed relevant literature and patents, including *Development of an Intelligent Soilless Cultivation Device*, *A Greenhouse CO2 Fertilization Control System and Method*, and *A Planting Cabinet*, among others. Building on this research, we designed a household smart hydroponic system around an STM32F1-series ARM controller, integrating multi-parameter environmental monitoring (temperature, humidity, light, pH/$CO_2$) with precise water and nutrient control in a single home-scale soilless cultivation system, using a touchscreen for the user interface. Compared with existing solutions, our design offers higher integration, lower power consumption, and better suitability for home use. The main points of innovation are:

1. **Photosynthesis-optimized lighting control based on the plant growth cycle.** The system accounts for how light intensity and temperature requirements differ across germination, seedling growth, and flowering/fruiting stages, dynamically adjusting these parameters to maximize photosynthetic efficiency at each stage.

2. **An integrated control strategy based on a root-growth model.** The system models how root growth responds to varying water and nutrient conditions, then adjusts control parameters across multiple dimensions based on that model.

3. **Intelligent nutrient-concentration sensing and control.** Sensors continuously monitor nutrient solution concentration; combined with known nutrient needs at each growth stage, the system automatically triggers dosing or dilution to keep concentration within a suitable range — avoiding both root burn from over-concentration and stunted growth from under-supply.

### 2.2 System Design

The system consists of four main modules: a core control module, an environmental sensing module, an actuator module, and a human-machine interface module. The core control module is built around an STM32F103C8T6 microcontroller connected to a touchscreen; it reads sensor data over serial communication, processes it, and drives the actuators accordingly, forming a closed "sense–decide–act" control loop on a 10-minute cycle, while logging data to support later analysis.

## 3. Technical Approach

The project moved through five stages: design → hardware selection → module testing and development → full-system integration and calibration → operation and optimization. We first settled on an overall plan, hardware configuration, and structural design; then selected sensors, the controller, actuators, plant species, and the growing rack; next, we tested each sensor and actuator individually for correct communication and function; after full assembly and firmware upload, we ran water-circulation tests and joint tuning of the automatic controls; finally, we ran short- and long-duration trials, observing plant growth and validating that the collected data was reasonable, using the results to keep refining the control strategy.

On the hardware side, the system is built around an STM32F103VET6 (Cortex-M3 core, 72 MHz), with 3 USART channels, 2 IIC, 3 SPI, and a 16-channel 12-bit ADC: USART1 handles real-time communication with a host computer, USART2 drives the touchscreen, and USART3 acts as an RS485 bus master polling the $CO_2$, temperature/humidity, and dissolved-oxygen/pH sensors. Four PWM channels drive the LED strips, water pump, and fan with stepless speed control, while GPIO pins drive a relay module to switch the humidifier, pH-balancing pump, and aerator on and off. On the software side, a unified serial command set (PWM speed commands, PE-pin switch commands, and CMD-style RS485 bus commands) handles parsing, execution, and status feedback. The touchscreen interface has five pages — Home, Environment Monitor, Water Monitor, Airflow Control, and Light Control — supporting both automatic control and manual override.

# 4. Results

## 4.1 Experimental Design

The experiment ran from October 1 to December 1, 2025, in a space designed to simulate a typical home balcony environment — including limited light and restricted airflow, conditions common to urban homes. The system (the "smart" group) and a control group were placed on the upper and lower tiers of the growing rack: the smart group used the STM32 control system described above, with automatic supplemental lighting, ventilation, and humidity control; the control group relied solely on natural light and ambient airflow, with no active adjustment. We chose butterhead lettuce as the test crop, six plants per group, germinated simultaneously and matched for seedling condition. The smart group automatically logged environmental parameters (air temperature, humidity, light intensity, CO2) and water parameters (nutrient solution temperature, dissolved oxygen, pH) every 10 minutes, with a full record saved every 30 minutes.

## 4.2 Data Analysis

**Light control:** Using the light compensation point (~2000–3000 lx) and light saturation point (~20000–30000 lx) for leafy vegetables as reference, the system set a dynamic supplemental-lighting threshold. When natural light fell below 3000 lx, the controller adjusted the PWM duty cycle of the white and red LED strips, boosting illumination to an effective photosynthetic range of 1000–8000 lx during low-light periods and adjusting light quality by growth stage — significantly raising the total daily light integral (DLI).

**Dissolved oxygen:** The dissolved-oxygen ratio and absolute dissolved-oxygen readings tracked closely together, staying fairly stable through the early and middle stages of the trial with some fluctuation later on — indicating that the aeration system kept the water reasonably well-oxygenated throughout.

**Temperature and humidity:** Fan cycling was one of the key drivers of environmental change — after the fan switched on, the temperature sensor typically showed a small but clear drop within a short window, while increased airflow also promoted moisture dispersal, helping regulate humidity. This threshold-based response reflects the system's ability to actively maintain a stable growing environment.

**CO2, pH, and humidity together:** All three parameters stayed relatively stable through the trial. CO2 concentration followed a stepped control pattern and remained within an effective range for photosynthesis; pH stayed within a narrow band near neutral; and humidity stayed within a comfortable range for the crop — together forming a balanced "air–water–moisture" system. After nine weeks of comparison, plants in the smart group had visibly deeper green leaves, sturdier stems, and more developed roots; the control group had a lower survival rate and weaker surviving plants, indicating that coordinated control of light, temperature, air, and water meaningfully supported healthy plant growth.

# 5. Discussion

## 5.1 Effect of Light Color on Plant Growth

We compared the spectral characteristics of white and red LED lighting: white light was the most balanced light source for promoting plant growth overall, while red light's spectral properties showed some value for cultivating small plants in low-light conditions and for boosting photosynthesis specifically.

## 5.2 Multi-Sensor Communication over RS485

The humidity sensor, $CO_2$ sensor, and the combined 3-in-1 sensor all share a single RS485 bus, but all three ship with the same default address (0x01). Left unaddressed, a command from the master device would trigger a response from multiple sensors at once. To resolve this, we reassigned the slave addresses of two of the sensors (to 0x02 and 0x03), which allowed all three devices to communicate reliably and concurrently on the same bus.

## 5.3 Feedback from Use in STEM Education

The system was piloted with a group of Year 11 students at our school, who used it to observe plant growth, adjust environmental parameters, and log experimental data. Feedback showed the system successfully sparked student interest in plant physiology, embedded systems, and data science, though some students found the underlying sensor principles and control logic difficult to grasp at first. We plan to develop a staged curriculum that moves from simple "observe and record" activities toward more advanced "program and control" tasks.

# 6. Conclusion

This project set out to meet the practical needs of small-scale home hydroponics and succeeded in building a system suitable for home-level validation and use. Its core strength lies in how closely it fits the target scenario: rather than adopting the complexity of large-scale production systems, it was purpose-built for balcony- and indoor-scale growing, with a form factor, workflow, and control logic that match how a typical household would actually use it — significantly lowering the barrier to entry. The system meets the core needs of home hydroponics, automatically monitoring and adjusting nutrient concentration, water temperature, and dissolved oxygen, and reliably supporting a full growing cycle for common crops such as lettuce and herbs.

The system still has clear limitations. First, its suitability for large-scale production has not been validated — the hardware and control algorithms were designed specifically for a small home environment and are not yet ready for greenhouses or commercial growing operations. Second, long-term stability and accuracy need further work: some core sensors are prone to data drift after extended continuous operation, and recalibrating them currently requires a trained operator, adding maintenance overhead that runs counter to the low-maintenance expectations of home users.

# 7. Summary

The main points of innovation in our household smart hydroponic system design are:

**Multi-parameter control:** Combining embedded systems with multi-sensor fusion, the system achieves precise monitoring and intelligent control of the hydroponic environment, addressing a gap in low-cost, high-precision equipment for home and small-farm hydroponics.

**A stackable, multi-tier structure:** The rack can flexibly gain or lose tiers depending on the available growing space, making efficient use of vertical space and adapting well to balconies and other small indoor growing areas.

**Strong practicality:** By pairing standard controls with a touchscreen interface, the system is simple and intuitive to operate, works well for non-specialist users, and supports a fully automatic mode — while still exposing interfaces for advanced users and further development.

**Educational value:** The project gives secondary school students a hands-on STEM platform, letting them observe a plant's full life cycle from growth to decline, and helping build scientific literacy and practical skills.

Given constraints on time and prior knowledge, the system still has plenty of room to grow. Future plans include adding networking and machine-learning components to build an adaptive model that maps growth stage to optimal environmental parameters for more precise automated management; adding a remote-monitoring module and companion mobile app so users can check data, receive alerts, and perform basic actions remotely; and continuing real-world trials to expand the system's dataset and add presets for a wider range of crops.

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