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SMART CLOSED-LOOP HYDROPONIC FARMING: AN IoT-BASED EDGE-INTELLIGENT FRAMEWORK FOR NUTRIENT MANAGEMENT AND WATER CONSERVATION

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Abstract

Hydroponic farming allows the growth of crop plants without any soil and provides them with nutrients through water. The technology is useful in situations where space is lim-ited or the growing conditions are easily controllable. However, its success is subject to strict control over water and nutrition supply. Control is complicated when the pH or EC changes, due to sensor drift, or firstly introduced nutrients are not yet mixed in the tank. A controller based merely on preset thresholds will react too quickly, while a cloud-based system would be less efficient in the case the internet connection is lost. This work integrates pH and electrical conductivity sensing, local processing of the data, and fuzzy-logic-enabled decision-making for nutrient application. The controller keeps track of the solution variables and implements the corrective measures within the specified boundaries, as well as controls the pumps for nutrient application while providing several very important functions locally even when the internet is absent. Flow measurements are included to have information about the inflow of the water, the recirculation process, and losses. The proposed system takes into account calibration, mixing time, limitations of the dosage, and maintenance of the sensors. The project's summary in-dicates that the target of 95% water retention is a goal to be achieved experimentally, not an accomplished result. The paper discusses the architecture proposed, workflow of control, eval-uation indicators, and the points to be considered for the implementation of resource-efficient hydroponic systems.

Keywords : Hydroponics, Internet of Things, ESP32, edge computing, TinyML, fuzzy logic, pH monitoring, electrical conductivity, closed-loop control, water conservation

Introduction

Hydroponics is a technique for growing crops without soil in which water and nutrients are dissolved in a suitable medium. It is appropriate for use in indoor farms, greenhouses, verti-cal farms, and countries that do not have enough arable land. Many recent reviews highlight the resource management aspect of hydroponics, stating that system work model and param-

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eters impact operation quality performance. [3–5]. Successful operation requires attention to solution chemistry, circulation, and equipment condition.

There are two essential parameters: pH and electrical conductivity (EC), where pH is an indi-cator of how acidic or alkaline the solution is, and EC refers to the indirect measurement of the concentration of dissolved ions. If the pH and EC values are outside the recommended range for a certain crop-growth stage, it may affect the need for nutrients as well as plant condition. This means that the target values need to be defined using agronomic knowledge and verified in practice. Being quite extensive in terms of work required, manual observations are not very efficient and simple threshold controllers may fail in the event of noise in readings or measure-ments that have not yet reflected the presence of the chemicals added. Cloud-based methods of monitoring may lose many functions if access to the internet is interrupted.

This system presented consists of an ESP32 microcontroller that measures the nutritive solution and carries out the control processes locally. The system is also applied with sensor filtering, fuzzy-logic dosing, flow counting, and, if needed, IoT performance. The primary aim of the system is to perform certain measures regarding the monitoring and safety operations irrespec-tive of internet connection, while remote monitoring is also enabled whenever required.The main objectives include:

- filter and calibrate pH and EC sensor readings locally;
- design an offline-first controller that preserves essential monitoring and safety functions during network interruptions;
- investigate fuzzy logic assisted dosing that considers deviations from target values and avoids repeated actions during mixing delays; and
- define evaluation measures for water containment, nutrient stability, control behavior, and system reliability.

The present work finishes with a design and evaluation plan. As the prototype has not been tested experimentally in the provided material, the claims on performance remain to be verified.

Background and Related

Work IoT-Based Hydroponic Monitoring

The IoT technology enables the communication of the basic elements relevant to environmental conditions for plant growth. For example, a hydroponic environmental monitoring system can record parameters such as pH, EC, temperature, water depth, and water flow. The recent studies conducted on ESP32-based systems show that the usage of these devices can facilitate the process of monitoring the conditions and utilizing irrigation pumps, while at the same time confirming problems related to the extents of scalability and interoperability. [1,2,6]. Telemetry can help operators identify abnormal conditions and review system history, but essential local safety functions should not depend entirely on a remote server.

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Edge Computing and TinyML

Edge computing allows data to be processed near the sensors and equipment acting on them. This can happen without every decision requiring the involvement of remote servers. In hydro-ponics, local processing lessens reliance on the availability of networks and eliminates time de-lays associated with remote inference. TinyML refers to methods of deploying small machine-learning models on resource-constrained devices. Whether a model can be supported on an ESP32 depends on its memory requirements, sampling rate, and computation load. In recent reviews, AI and IoT have been suggested as areas that promise a way for facilitating smart hydroponics while noting that deployment maturity and integration are still uneven. [2, 3]. In this framework, fuzzy inference is the primary proposed control method; a learned model is a possible future extension rather than a feature claimed to be already implemented.

Closed-Loop Nutrient Control

In a closed-loop control system, constant supervision of the entire process is done, the results are compared, and it is determined whether any adjustment is required. As for hydroponics, it may involve switching on the systems that supply nutrients or sending signals to the farmer in case the pH or EC levels are not within the stipulated limits. It is necessary to consider the calibration of the sensors, the rate of the pump, the concentration of substances and the duration of the mixing. There is already literature on the use of rule-based, fuzzy and IoT-supported methods for regulating the parameters; however, all these aspects have to be examined in detail with respect to specific crops and specific systems. [7, 8, 11]. Excessive dosing can destabilize the solution and may harm plants.

Fuzzy Logic for Agricultural Control

Fuzzy logic depends on describing categories like low, close to the ideal value or high and then drawing up a rule to develop a mechanism. This approach can be useful in implementing efficient control policies in the absence of a full physical model. However, design of the mem-bership functions and rules must be done carefully, including the assessment of the range of values and testing.

Insights from the Project Synopsis

The summary of this project includes several directions which may prove relevant: monitoring using EC and pH sensors based on ESP32, cloud telemetry based on MQTT, creation of fuzzy inference techniques for nutrient management, and promotion of recycling strategies. It also points to some of the major limitations which the project seeks to address: sensor failure, de-pendence on the networks, certain limitations in processing, dead times in mixing, and lack of auto-calibration. Prior to submission, bibliographic information should be matched with pub-lishing or indexing data, and citations provided here cannot be interpreted as valid experimental data in their own right. The related literature reviewing some IoT monitoring solutions, ESP32 implementations, fuzzy control and knowledge-based control commercial project implementa-tions, nutrient management methods, water efficiency, and sensing techniques [4, 5, 13].

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Research Gap and Motivation

The proposed work is motivated by four practical issues.

Dependence on Remote Services

If essential control actions require cloud access, network interruptions may prevent normal monitoring or dosing. A local fallback mode can preserve selected functions without an active internet connection.

Mixing and Response Delay

The reading taken right after the medication might not be an accurate indication of the fully mixed status of the reservoir. Reacting to every minor fluctuation leads to unnecessary infusion of chemicals. Thus, the controller has to let a specified period of time go by before measuring again to conclude whether an additional adjustment is required.

Sensor Drift and Fouling

Continuous immersion can change a sensor's response over time. Calibration, cleaning, plau-sibility checks, and maintenance reminders help reduce the risk of making control decisions from inaccurate measurements.

Limited Resource Accounting

Claims about water conservation should rely on actual measurements of water entering the system, water recovered or recycled, water added through use, and water lost through leaks, discharge, or any other mechanism. The use of flow measuring devices in conjunction with a well-defined accounting boundary will be necessary for making meaningful assessments. The proposed architecture includes these issues; however, actual proof of benefits remains to be obtained through experimental testing.

Proposed System Architecture

A display board presents real-time measurements of acidity and conductivity, sensor status, total amount of water flowing, the condition of pumps, alerts, and trends from the past. It should be able to tell the difference between the current data and faulty or outdated data.

Sensing Layer

Improving safety features and performance of the system requires integrating additional sen-sors. The temperature of the work medium and the amount of liquid in the reservoir can be measured by additional sensors. It is important that the signals provided by the sensors are compatible with the ESP32 electrical specifications. Depending on the type of probes used, signal conditioning and electrical isolation may be required.

Edge Controller

The ESP32 gathers data from the various sensors then filters and calibrates that data, counters the validity of the reading, and executes the local control process. It also controls based dosing pumps

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according to safety constraints.

Dosing and Circulation Layer

Micro-peristaltic pumps can be utilized to add nutrient concentrates or pH corrective solutions, while in the circulation pump liquid is transferred from the reservoir or hydroponic channel. Dosing channels must provide for the segregation of incompatible concentrates. It is essential that the software controls the duration of each pump-pulse, intervals between dosing operations.

IoT Communication Layer

With an optional connection to the MQTT platform, information about measurements and alarm conditions can be communicated to the dashboard. Commands from a remote loca-tion must be authenticated and verified. In case of a network failure, the internal controller will continue working safely and save the latest measurements in the memory, provided there is enough memory available.

Monitoring Interface

The display board shows current acidity and electric conductivity, the state of the sensors, the overall stream, the state of the pump, and any warnings as well as old tendencies. It must be able to tell the difference between normal functioning and faulty or old sensors. Fig. 1 summarizes the proposed feedback loop.

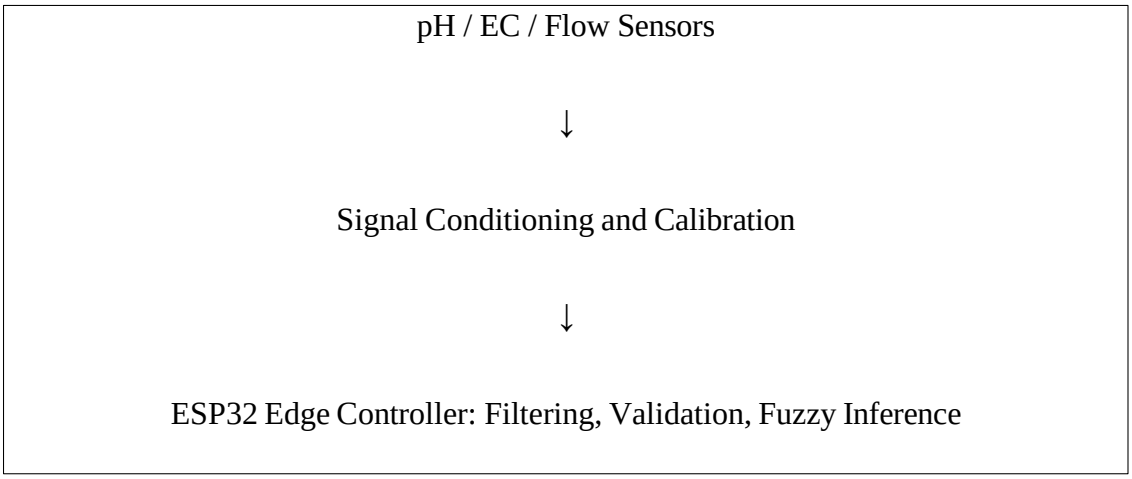
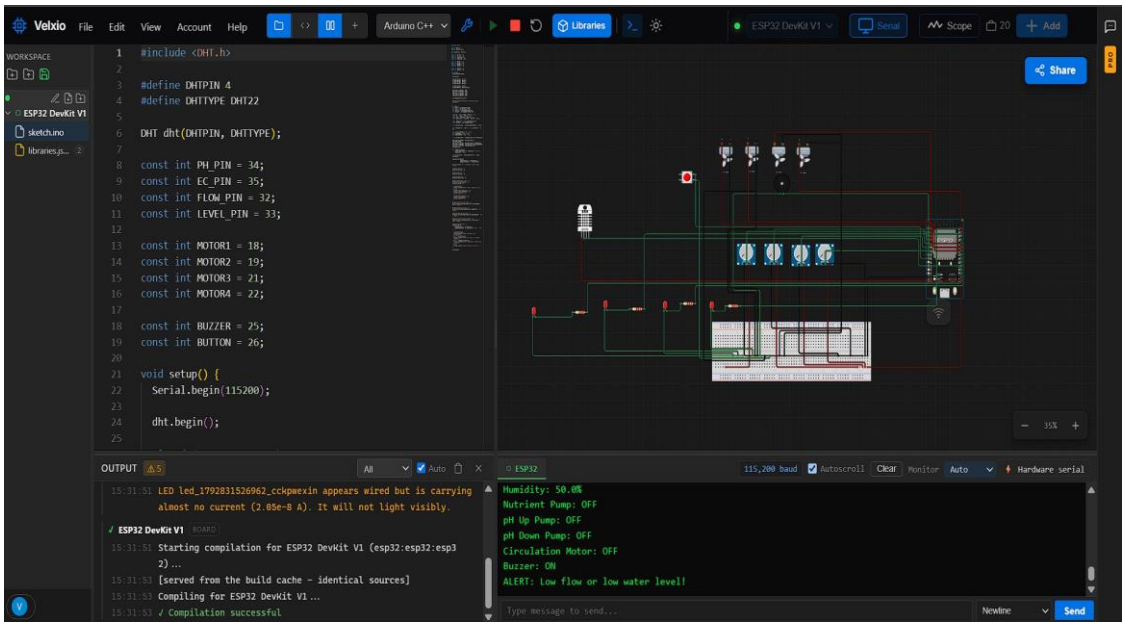


Figure 1: Proposed conceptual framework for the hydroponics control system. The figure here re-pres-ents the design schematic, however, not the working model.

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Sensor Processing and Calibration

Low-Pass Filtering

Electrical noise and transient changes may be contained in sensor signals. A first-order expo-nential filter can smooth the measurement stream:

$$\hat{x}_k = \alpha x_k + (1-\alpha)\hat{x}_{k-1}, \tag{1}$$

where x_k is the raw measurement at sample k, $\hat{x}_k$ is the filtered value, and α is a coefficient between zero and one. The choice of α determines the trade-off between noise suppression and response speed. Filter parameters should be selected through sensor tests and consideration of reservoir dynamics.

Calibration

The pH and EC sensors should be calibrated with suitable reference solutions according to the manufacturer's instructions. A generic linear calibration model is

$$x_{\text{cal}} = a x_{\text{raw}} + b, \tag{2}$$

The records for calibration must have all pertinent information including date, reference values, and sensor identifiers. Instances where the readings fall out of the specified limits must be indicated as invalid with no concern for dosing purposes.

Sensor Health Checks

The controller should detect disconnected probes, implausible jumps, stale data, and readings that remain unchanged for an abnormal period. When it is determined that a critical sensor is

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invalid, automatic chemical dosing must be disabled or moved to a known safe condition and an alarm raised as appropriate.

Fuzzy-Logic-Assisted Dosing

Input Variables

The suggested fuzzy controller takes the distinction between a measured value and its objectives into consideration.

For EC, the error is

$$e_{pH}(k) = pH_{target} - pH_{measured}(k). \quad (3)$$

$$e_{EC}(k) = EC_{target} - EC_{measured}(k). \quad (4)$$

Target values must be configured for the selected crop and growth stage using appropriate agronomic guidance. A single universal target should not be assumed for every crop or nutrient formulation.

Fuzzy Sets and Rules

Mistakes fall into categories of low, close to target, and higher error. The membership functions convert numbers into degrees of membership. The fuzzy inference system evaluates the rules and then gives the output value with boundaries.The following rules serve as examples:

- If EC is below its permitted range and the sensor readings are valid, request a small nutrient correction.
- If EC is within the configured range, do not add nutrients.
- If pH is outside its permitted range, consider an appropriate correction only after sensor validity and dosing safety have been checked.
- In case of pump fault or invalid sensor status, stop automatic dosing, and activate an alarm. These regulations are theoretical. The final set of regulations must provide specific details on the ways of making a correction, limitations concerning different crops, scaling of the output, and interrelations between pH control and EC control.

Dosing Limits and Mixing Delay

The controller should not dose continuously in response to each measurement. After a bounded pump pulse, it should wait for the solution to mix, take new measurements, and evaluate the result. A further correction may be considered if the value remains outside the permitted range and cumulative dosing limits have not been reached. Dosing volume can be estimated from a calibrated pump flow rate:

$$V_{dose} = Q_{pump} t_{on}, \quad (5)$$

where Q_{pump}represents the flow rate of the pump, and ton represents the activation duration. Volume delivered requires validation since flow rate of the pump may vary due to tubing, pres-sure, abrasion, and

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fluid characteristics.

Proposed Control Algorithm

Inputs: Calibrated pH and EC readings, flow readings, target ranges specific for crops, and performance criteria..

Outputs: Updated status, bounded dosing actions, and alarms.

1. Initialize the ESP32, sensor interfaces, pump outputs, local configuration, and communi-cation service.
2. Inquire about acceptable limits of dosing of any crops, as well as their target levels of pH and EC.
3. Check readings of pH, EC, flow, and supporting sensors.
4. Apply calibration and low-pass filtering to the correct readings.
5. Evaluate the controller, credibility of measurement results, state of reservoir and opera-tion of pump.
6. If the controller fails or safety measures are violated, stop the dosing, write to the log about the breakdown and issue a local alarm.
7. Otherwise, calculate pH and EC deviations from their target ranges and apply fuzzy inference rules to estimate a bounded correction.
8. Check the requested action against pump limits, dosing intervals, and cumulative chemi-cal limits.
9. If possible, turn on the respective pump for the needed time and wait till the end of the process.
10. Update flow totals and local logs; publish telemetry when connectivity is available, and repeat the cycle regardless of internet status.

This algorithm is a design proposal. Pump interlocks, chemical compatibility, and crop-specific operating limits must be verified before deployment.

Water Conservation and Resource Accounting

The synopsis for the project defines the achievement goal for the project as 95 percent water retention results. The boundaries of the system and the criteria for defining water retention need to be clearly stated before measurements can be conducted. It is necessary to calibrate the flow meters, synchronize the readings, and make sure that the time of watching is long enough so that it includes normal work, cleaning, and refilling. For a defined accounting period, a water balance can be written as

$$V_{\text{in}} = V_{\text{recovered}} + V_{\text{loss}} + \Delta V_{\text{stored}}, \quad (6)$$

where V_{in} is measured input volume, $V_{\text{recovered}}$ is the volume collected or reused under the study's definition, V_{loss} is measured or estimated loss, and ΔV_{stored} is the change in stored water volume. Terms

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must be defined consistently to avoid double-counting and to reflect the selected system boundary.

If containment is defined as the fraction of input water recovered or retained for the intended process, it may be expressed as

$$C_{\text{water}} = \frac{V_{\text{recovered}}}{V_{\text{in}}} \times 100\%. \quad (7)$$

This metric is appropriate only when the protocol clearly defines recovery and accounts for storage changes and other relevant flows. Plant uptake and evaporation should be reported separately where possible. The 95% figure is a target from the project synopsis, not a result established by this paper. It is necessary to calibrate the flow meters, synchronize the measure-ments, and have sufficient observation durations so that normal use, cleaning and refilling can take place.

Implementation Considerations

Hardware

The hardware that is suggested comprises an ESP32 controller, the necessary components for pH and EC level detection, a set of metering pumps, and a pump for water circulation. Com-ponents should be selected according to prototype scale and chemical compatibility.

Software

The firmware is aimed at data accumulation coming from sensors, data filtering and calibra-tion, application of fuzzy logic to obtain results, identification of the pumps' operation times, management of emergency situations and data logging.

Offline-First Operation

Internet loss should not interrupt local sensor sampling or basic safety logic. Remote dash-boards may become temporarily unavailable, but the controller should continue using its local configuration. Buffered records can be synchronized after reconnection if storage capacity and data integrity permit.

Safety and Maintenance

The dosage should be constrained according to the persistent duration of the pulse and the total axis of the amount. The device must incorporate features for manual control, cutoff of the pump, as well as the safety of the units which were calculated improperly. The chemicals should be kept and used in a proper way. It is necessary to clean and calibrate the sensors from time to time.

Evaluation Methodology

It is crucial to test the system in laboratory circumstances with a defined basis before making any claims on water savings and the effects on plants.

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Nutrient Stability

Record pH and EC at fixed intervals and compare the measurements with crop-specific target ranges. One useful metric is mean absolute error (MAE):

$$\text{MAE} = \frac{1}{N}\sum_{k=1}^{N} |y_k - \hat{y}_k|, \quad (8)$$

where yk refers to the provided or final value, ˆyk refers to the observed or calculated value in line with the chosen measurement method, and N is the quantity of experiments.The study needs to specifically clarify what quantity is being used as the reference. Other variables can be evaluated in the process of assessment as the time taken for non-permitted states, time taken to return to balance after interference, project number, and other parameters.

Water-Use Evaluation

The input of water, volume of water captured, changes in the reservoir levels, and the process of refilling and discharging should be measured during a specified time period. The controlled system ought to be evaluated against a well-recorded background under similar circumstances of growing, surroundings, and running.

Offline Reliability

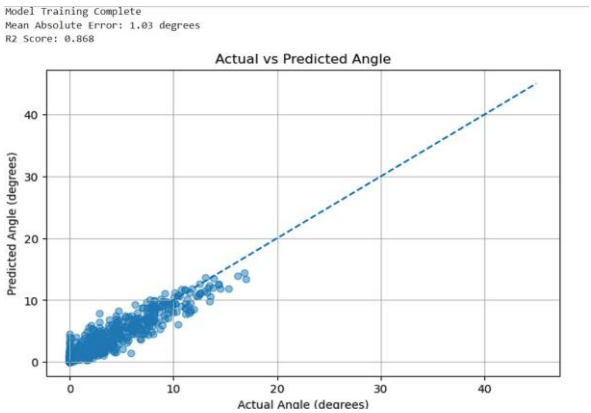
Disconnect the internet under controlled conditions and verify whether sensor acquisition, local control, safety interlocks, and logging continue. Record missed samples, fault responses, and recovery behavior.

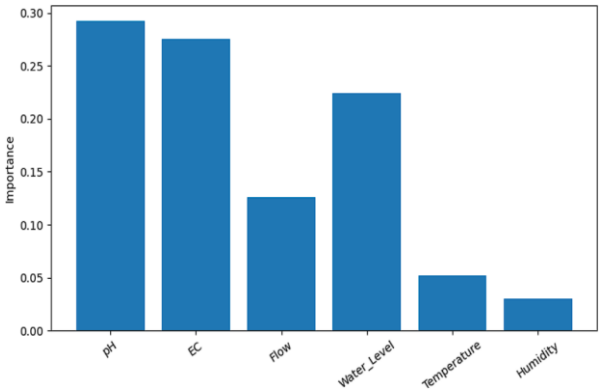
Sensor Drift

See whether the readings of sensors agree with the measurements by standard equipment at set time periods and register any differences in readings before or after the process of cleaning and calibration.

Experimental Reporting

When finalizing your study, ensure that the number of tests, capacity of the reservoir, type of crop, type of sensor used, frequency of sampling, measures taken by the controller, calibration process and external





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conditions are reported. Results should include suitable uncertainty es-timates and comparisons with a baseline. No measured performance values are claimed here because the supplied material does not provide experimental datasets or prototype results.

Expected Benefits and Limitations

The architecture described here provides a method to control solution chemistry, eliminate ex-cessive dosing, and provide local solution control during network interruptions. Flow measur-ing makes the claims about water usage practically verifiable, while the local logging function provides support for troubleshooting and repairs. Note that these advantages are not guaran-teed. Indeed, results depend on sensor properties, calibration, controller features, pump preci-sion, mixing, and plant-specific configurations. Fuzzy logic cannot overcome the inaccuracies of measurements and principles. The ESP32 platform may also have problems with memory and processing resources when operating more advanced machine-learning algorithms. Lastly, water conservation must be measured with a proper accounting method: high recirculation does not mean that all water can actually be reused.

Future Scope

Future work may extend the framework by:

- implementing and testing automatic calibration and sensor-drift detection;
- comparing fuzzy control with fixed-threshold and other suitable control strategies;
- investigating compact machine-learning models when suitable datasets and embedded re-sources are available;
- adding temperature, water-level, and additional flow sensors to improve system-state esti-mation;
- evaluating nutrient consumption, crop growth, energy use, and water balance over longer cultivation cycles; and
- exploring root-image analysis and anomaly detection as optional monitoring capabilities.

Conclusion

The research paper explains a possible solution for smart hydroponic management utilizing an ESP32 controller, pH and EC sensors, local signal processing, dose management based on fuzzy logic and flow measurements. The whole system is designed in a manner to monitor the system locally and provide control within the limited framework without continuous internet connection. The system is proposed taking into account specific practical issues mentioned in the project synopsis such as sensor drift, chemical mixing delays, dependence on the cloud and the need for water accounting. The paper also describes the workflow and measures adapted for measuring stability of nutrient solution, dosing behavior, reliability offline and water con-tainment. The figure with 95% of water containment is mentioned as a proposed value that shall be calculated via specific calibration. The proposed methodology shall be used in the future to create prototype and document both hardware and software and run an experiment on controlled environment and produce data in case to draw conclusions.

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