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IOT-BASED HYDROPONIC UNDER WATER FARMING SYSTEM

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ABSTRACT:

The paper shows a smart hydroponic lettuce growing machine that will be based on the Internet of Things (IoT) architecture, and it will resolve the resource inefficiencies and uncertainty of the traditional soil-based agriculture. The system cultivates lettuce in a nutrient-charged water culture - completely without soil - and makes use of an assortment of internal sensors to keep a steady check on key growth parameters. At its core is an ESP32 microcontroller that gathers measurements of dissolved oxygen readings, electrical conductivity measurements, temperature, and ambient light measurements in real-time. The data obtained is wirelessly sent to the Blynk cloud platform where growers can view, analyze and act on plant data live via a smartphone interface regardless of their location. The automated signals inform users whenever measurements fall within the predetermined safe limits, and physical monitoring is thus eliminated virtually. The closed-loop nutrient delivery system saves water by returning the solution at the end of the growing cycle, which significantly saves water as opposed to the conventional irrigation. The results obtained by the experimenters prove that the yields of lettuce, evenness of growth, and use of resources are significantly increased compared to the manual system of hydroponics. The results locate this IoT-ized system as a real-world, scalable system in precision agriculture and urban food production.

KEYWORDS: Internet of Things (IoT), Hydroponic Cultivation, Lettuce Farming, Smart Agriculture, ESP32, Dissolved Oxygen Sensor, Electrical Conductivity, Blynk Platform, Precision Farming, Urban Agriculture, Real-Time Monitoring.

I. INTRODUCTION

There are a number of forces converging in modern agriculture, including the reduction in the size of arable land, unpredictable rainfall distribution, a skyrocketing urban population, and increasing resource use efficiency. The traditional approach to soil farming, though common and widespread, has a hard time reacting fast to these issues. The use of water, precision of nutrient delivery, and responsiveness to weather changes are all common problems with farmers at both large and small scales [1], [2].

Hydroponic production assures some of these issues with soil left out of the equation. Plants are either growing in an inert media or directly above a flowing nutrient supply, therefore it is straightforward to control exactly what individual plant gets and when. Decades of research has demonstrated that hydroponic crops can grow more quickly, consume less water compared to field-based agriculture and yield more per unit area [3], [4]. These benefits also render hydroponics particularly appealing in rooftop gardens in urban areas, controlled-environment agriculture, and in water-constrained areas.

Although promising, manual inspection continues to play a significant role in most small and mid-scale hydroponic facilities. Growers need to check the nutrient levels, the water pH levels, water temperature and the dissolved oxygen levels regularly- a tedious job that presents chances of human error and late remedial measures. The adoption of the Internet of Things (IoT) technology has a promising solution. Sensors are networked, which means that they are able to gather data on a continuous basis, microcontrollers are able to run that data in real time or cloud platforms are set to make that data available to the farmers wherever they travel [5], [6].

The given paper presents the description of an IoT-based hydroponic system that is tailored for lettuce, a short-cycled commercially significant leafy crop that is known to be highly sensitive to nutrients and environmental factors. The suggested system combines an ESP32 microcontroller, dissolved oxygen, electrical conductivity (EC), temperature, and light-intensity sensors. Information travels wirelessly to the Blynk platform where there is a live dashboard presented on any connected smartphone. In case of readings out of the target windows, alerts are raised and in some settings, the system activates corrective actuators.
automatically. The outcome is a low maintenance, informative growing system that answers precision-agriculture mindfulness to small-scale urban farmers [7], [8].

II. PROBLEM STATEMENT

Even traditional hydroponic systems, which may be constructing based on good agronomic principles, still have the same inherent vulnerability, namely lack of sustained, automated check-ups. A grower who measures parameters of nutrient solutions twice a day can fail to notice a six-hour interval in which dissolved oxygen levels fell below the root-damaging threshold, or in which a failed pump caused the level of electrical conductivity to shoot up to power-damaging levels. When the anomaly is detected by manual inspection, the crop has already started to be damaged.

Tele-accessibility adds to the issue. Urban gardeners have numerous locations or may operate a garden as a part-time job in addition to taking out full-time jobs. The fact that checking the crop conditions is impossible without physically visiting the site results in such situations where an issue like a slightly increased EC, a slow increase in temperature, or a problematic light timer is not noticed in time.

Currently available consumer-level hydroponic kits do not fill any of these monitoring gaps. They offer physical equipment (reservoir, pump, grow tray) but all sensing and response is to the grower. There are more advanced commercial systems available, but their cost and complexity are beyond the reach of amateur hobbyists or school projects, or even low-income urban agriculture projects.

This gap is bridged by the system presented in this paper, which deploys low cost and easily accessible sensors and an ESP32 microcontroller and links the complete system to the Blynk cloud platform. The combination provides 24/7 environment monitoring, dashboards accessible to smartphones, and optional alerting limits - without growers having to invest in expensive proprietary hardware and specialized software knowledge.

III. Practicality of proposed IOT-enabled HYDROPONic Lettuce System in contemporary Agriculture.

The lettuce crop yields almost 27 million tonnes daily around the globe and its demand is constantly increasing due to increased participation of the consumer in the consumption of fresh and locally grown products. A lot of this lettuce is still cultivated in open fields where it is prone to attack by pests, to water pressure, and to extremes of temperatures. The prospect of year-round, weather-independent production is accessible using controlled-environment agriculture (and hydroponics specifically) though this can only be accessible as long as the extra complexity of controlling nutrient solutions is effectively managed.

The IoT incorporation changes the management equation. Instead of having to use the schedule and sense used by a grower, a networked system records objective, time-stamped data on all important parameters. Trends become visible. Minor defects are before they grow big. One can optimize on the energy used by making light hours proportional to growth rates. When the reservoirs drop up to a certain level, water replenishment can be automatic.

In the case of urban agriculture, remote-monitoring possibility opens up new opportunities. Something can be looked after on a different floor in the same building - or in another neighborhood altogether - because of a rooftop installation in a crowded city neighborhood. Participants can be engaged in community gardens and school greenhouses without all participants being available at specific times.

The proposed system is therefore not only a technical convenience; it is an enabling technology to social and structural change in the process of food production in cities.

IV. Used tools and technologies.

The system is based on a specifically small technology stack selected due to affordability, community, and integration. An ESP32 microcontroller is a dual-core microcontroller with the following features: concurrent sensor polling, data formatting, and Wi-Fi transmission do not present a bottleneck to performance. It is programmed directly to the Arduino IDE with a time-tested set of C/C++ sensor-driving libraries and Blynk client SDK.

A DS18B20 waterproof temperature probe measures the warmth of the solution on the sensing side; an oxygen-like probe with a gravity-type sensing element measures the oxygen level in the solution, a conductivity probe detects the level of total dissolved solids which is an EC value; and a BH1750 light sensor measures the abundant photosynthetic-active radiation at the canopy. All these four sensors all give a clear picture of the environment surrounding the lettuce growth.

Blynk 2.0 platform deals with cloud connectivity. Blynk takes push data (from the ESP32 via HTTPS) and stores it in a time-series database, then displays it as customizable dashboards using widgets. The dashboard is accessed by the Blynk mobile app, both iOS-based and Android-based. Push notifications can be generated with event rules set within the Blynk console which detects sensor values exceeding user-defined thresholds and push notifications can be sent to trigger a responsive action, without the grower watching the dashboard all the time.

To achieve local logic and failsafe behavior the Arduino sketch on the ESP32 also drives a relay module which is able to open and close a peristaltic pump in response to the DO readings, to guarantee that even when not connected to the cloud a restart of water circulation (and hence oxygenation) happens automatically when readings fall below a critical value.

V. CORE COMPONENTS

A. ESP32 Microcontroller

The ESP32 (Espressif Systems) is the heart of the communications and processing in the system. It has two cores, Xtensa LX6, the ability to run sensor-polling routines and Wi-Fi communications at the same time. On-board 802.11 b/g/n Wi-Fi and Bluetooth support avoids the use of an external communications card and the hardware size and materials are minimal. The ESP32 has a low-power consumption of a few microamperes in deep-sleep mode and can be used in applications with power constraints due to its low power levels.

B. Sensor Suite

There are four sensors that are used together to define the hydroponic environment. One-wire digital temperature sensor, DS18b20 is installed inside a waterproof stainless-steel probe, which can be directly inserted into the nutrient reservoir. The gravity dissolved-oxygen sensor provides an analog voltage that is proportional to oxygen concentration of the solution - a factor that is closely associated with root condition and efficiency of nutrient uptake. The EC probe is used to measure the overall ionic strength of the solution, which is a proxy of overall nutrient strength. Lastly, the BH1750 I2C light sensor gathers light levels above the canopy of the plants and enables light schedules to be checked and anomalies (i.e. a broken grow-lights) detected instantly.C. Blynk Cloud Monitoring Platform

C. Blynk Cloud Monitoring Platform

Blynk 2.0 is an autoscaled IoT backend that does not need any self-hosted infrastructure. The ESP32 authenticates the Blynk cloud with an authentication token and publishes sensor data to virtual data streams with a non-negligent polling time (usually in 30 s). Blynk web console lets administrators create dashboard items (numbers, gauges, other historical line charts) and event rules which cause mail or push notifications. The mobile application is a replica of the web dashboard and it has control widgets like buttons and sliders which can call on/off commands to actuators attached to the ESP32.D. Nutrient Deployment and Hydroponic Buildings.

D. Nutrient Delivery and Hydroponic Structure

The culturing design consists of a deep-water culture (DWC): the seedlings of lettuce are cultivated in net cups suspended in holes in a floating raft made of polystyrene over the undercarriage: the root system of lettuce is suspended to an aerated nutrient solution. The solution circulation and oxygenation are kept by a submersible pump and air stone. The reservoir is covered to reduce evaporation as well as contamination. A float valve is used to top-up with fresh water automatically when the volume of the solution is low, and the peristaltic pump is used to add or take concentrated nutrient solution in special measured amounts when EC values are showing depletion.E. Controlling and Automation Logic

E. Control and Automation Logic

The Arduino program (firmware) uses a state-machine loop running after every 30-second interval. Each cycle reads all four sensors, calculates against set thresholds, and records a time-stamped message to the Blynk datastream and assesses whether or not any actuator action is necessary. Below the 5mg/L threshold, the air pump relay will run ten minutes with the aim of the remediation process. When EC is less than 1.2 mS/cm the nutrient dosing pump will transfer a constant amount of concentrated solution. These local control choices are not dependent on the level of internet connection and so, the crops are safer even during periods when there is no internet connection.

F. Power Supply

A 5 V, 3 A USB-C peripheral is used to power the system on a breadboard power rail. A regulation plate on a 7805 board provides a 5 V constant to sensor modules and the relay board. A relatively small solar panel packed with an 18650 lithium-cell battery pack, and a TP4056-based charge controller can be used to power off-grid applications to the full day-night cycle, outdoor or rooftop.

VI. LITERATURE REVIEW

The integration of IoT technology and controlled-environment agriculture has produced a considerable amount of literature throughout the last 10 years. Early on there were studies examining how wireless sensor networks can be applied to field crops showing that by automated soil-moisture sensing, an irrigation water usage reduction of 2040% on soils could be achieved without losses. With the lowered cost of sensors and more capability of microcontrollers, scholars started to employ similar principles to indoor and greenhouse environments.

Hydroponic systems turned out to be an intuitive choice to be monitored by IoT due to the closed-loop, controlled systems, where sensor data can be easily interpreted. Patil and Kale illustrated a WiFi-based system that measured pH and temperature in a small-scale NFT (nutrient film technique) system that allowed a multidimensional control of chemical aspects of the nutrient solutions, compared to periodic manual testing [5]. Kumari and Sood further developed this method by incorporating the actuator feedback whereby the automated pH regulation based on peristaltic dosing pumps revealed the continuous maintenance of the solution acidity within the range of +0.2 to -0.2 pH units, rather than +0.8 units, when left to manual controls only [10].

Blynk has been tried as a layer of middleware to agricultural projects involving IoT, in which a variety of organizations have found its combination of ease of access and capability to be appropriate. Blynk was integrated by Islam and colleagues with an ESP8266-controlled spinach hydroponic monitoring system to send reports in a mobile dashboard compared to a paper-log control group along with finding nutrient deficiencies 40 times faster [11]. Other characteristics of their work that were deemed useful especially in monitoring weekends and off-hours included the event-notification system.

Research into dissolved oxygen water dissolved in hydroponics is still not well understood though it is beginning to assume critical relevance as a component. The low oxygen (Less than about 4-5 mg/L) in the root zone vetoes nutrient uptake enzymes, and microclimate favorable to the water mold Pythium usually resulting in the death of hydroponic plants. Kumar and Singh have shown that among timer-only aeration strategies, a decrease in timers reduced the incidence of Pythium in lettuce by over 70-percent in the event of continuous DO tracking strategy with automated aeration control [8].

A further step towards smart hydroponic systems has been suggested to be machine learning and predictive analytics. A survey of the big-data applications in agriculture overall, conducted by Wolfert and colleagues, revealed that nutrient-management and predicting yield were applications, where historical sensor measurements, combined and processed with regression and deep-learning algorithms could be used to substantially reduce input wastes and production variability [13]. Kamilaris and Prenafeta-Boldu have recently surveyed agricultural-specific deep-learning models, which demonstrate good performance on plant disease classification with canopy images but note that the training data on hydroponic crops is scarce in comparison with field crops [14]. The system described in this paper has not been implemented with predictive analytics, but is designed in such a way, that it could be expanded to include the architecture of data logging in the future, which will then allow the addition of machine-learning into the system.

The literature gaps are: integrating EC and DO sensors to offer closed-loop nutrient and oxygenation on a cost-effective platform; introducing light-intensity sensor to monitor grow-lamps; and studies based on the newly introduced API of Blynk 2.0 platform, which is fundamentally different than the previous Blynk legacy platform present in most earlier studies. The present paper provides the answers to the three gaps.

VII. Outline of planned solution.

The proposed system will be comprised of the integration of a hydroponic system of DWC and an ESP32-powered sensor and control device and Blynk cloud platform into a coherent smart farming system. The architecture is designed to be modular: every single layer can be upgraded, or swapped, in response to future changes in technology or user requirements as the grower evolves towards physical growing structure, sensing and actuation, local control logic, cloud communication and user interface.

In the commissioning stage the grower establishes threshold parameters on each variable of interest (regulated by the Blynk console): target EC (1220 mS/cm range is recommended to grow lettuce), target DO floor (5 mg/L), range of solution temperature (1824 C), and the minimum number of light hours accrued per day. These values are read at boot, and stored in the non-volatile flash memory of the ESP32 firmware and will be used even when it is off-line, as they are stored in non volatile memory and read on-line.

In operation, sensor-polling loop is run at 30 s. Every cycle finds a rolling average 5 points of each parameter, and then proceeds to compare the values with thresholds to smoothen out any transient noise. When a smoothed value crosses a threshold, the firmware increments a violation counter; when the violation counter hits three consecutive violations (i.e., the condition has lasted 90 seconds) then the system sends both a local actuator response and a Blynk notification event. This type of hysteresis logic does not become alert by spurious means because of the individual noisy readings, but does become a actual problem within two minutes of its occurrence.

Blynk receives HTTPS Data in the form of formatted JSON packets. Historic data is stored in the Blynk console with free 90-day storage to free-tier accounts and the historic data itself is converted by the mobile app into interactive line charts. Growers can zoom into any period: the period in which the temperature was high, or the gradual decline of EC during a week as the vegetation used up nutrients and developed an exact management plan.

The closed-loop design promotes water and nutrient congruence. The reservoir is so big that it could hold seven days of nutrient volume of a typical raft of lettuce with a six plant. The use of float-valve top-up and EC-controlled dosing of nutrients suggests that the only physical exercise of the grower is weekly check-up of the reservoir and once or twice a month, complete replacement of the solution to remove the build-up of salts. The day to day maintenance is done automatically.

VIII. modeling and explanation of the Algorithms.

A. Layered Architecture

It has a hierarchical structure composed of four functional layers which deal with different aspects of the overall operation:

1) Sensing Layer — There is a constant sampling of the hydroponic environment by four sensors (DS18B20, DO probe, EC probe, BH1750), which give raw digital or analog data to the ESP32.

2) Processing Layer -The ESP32 code provides noise reducing, threshold comparison and actuator-control algorithms. Without relying on the availability of clouds, it maintains local state and react to anomalies.

3) Communication Layer - Wi-Fi component of ESP32 transmits the arranged sensor data within Blynk cloud in triumph of HTTPS at 30-second Peers. Connection routine A connection routine takes care of illegal connections to the network.

4) Application Layer - The web console and mobile dashboard of Blynk indicate the real time readings on the grower, historic charts and event logs. Actuators can be manually overridden when necessary by control widgets on the dashboard.

B. Operational Algorithm

The control loop of the system starts as follows:

1) Enable ESP32 peripheral (GPIO, ADC, I2C, OneWire busses).

2) Attempt to find a connection on configured Wi-Fi network, back-off until successful with exponential back-off.

3) authenticate with Blynk cloud; read existing threshold settings of virtual pins.

4) Start loop (30 second loop):

5) Read raw data of the four sensors.

6) Use 5 point moving average filter to reduce noise.

7)Compare filtered values with stored thresholds.

8) Bypassed parameter violation counter; set on parameter returned to normal.
9) When violation counter DO: 3 or more: turn on air pump relay 10 minutes.
10) When violation counter 3 or more EC: start nutrient pump to dose calculated period.
11) When counter (violation) of temperature or light = 3: notify via Blynk only (no actuator).
12) Publix current measurements and actuator positions to Blynk virtual pins.
13) The time-stamped data packet with data is logged to the Blynk datastream to store historical data.
14) Sleep remaining; repeat in step 5.
15) Wi-Fi lost: local control logic; buffer data packets; clear data packet queue on connection;

IX. PURposes of the proposed system.

This IoT-based hydroponic lettuce design is developed based on seven key goals:

Measure the four parameters that are most vital to the health of lettuce in a DWC hydroponic setting: dissolved oxygen, electrical conductivity, solution temperature and canopy light intensity continuously and automatically.

Facilitate remote monitoring and control where a smartphone was used, so that resorting to physical presence of growers in order to do so on a regular basis was not adopted.

Close the loop control of DO and EC actuators, which will reduce the rate of manual control to once per week reservoir monitoring and control.

Water-saving through recycling of the nutrient solution and automatic top-up are aimed to achieve a reduction of 50% water usage over equal amount of soil cultivation.

Offer transparent data logging that can be readily ingested later to analyse retrospectively and in future, predictive growth models can be trained.

To compare prices to school projects, community gardens, and smallholder urban farmers, have a bill of materials that is under about USD 40/unit.

Architecture Design to be modular, such that more sensors, actuators or AI-based analytics can be added, without having to redesign the hardware.

Forces of the Existing Approaches.

The conventional hydroponic systems do not include the monitoring electronics, placing all of the sensor load on the grower. Some functions are automated by a commercial sort of smart-farming system like Growtronics or Click and Grow, which are closed-box systems featuring proprietary hardware and recurring subscription charges, which are unaffordable to low-budget users. Literature prototypes of research are typically based on legacy Blynk server stacks or custom Flask/MQTT server stacks which need to be self-hosted on personal infrastructure and familiarity of the developer. The current system provides a grower warm and opensource strategy by bridging the void between the self-assembled and costly commercial systems at a low cost.

X. SCOPE Of the proposed system.

It is in the short-term perspective of the project when lettuce will be grown on one raft of six plants in a DWC, which will be a prototype that can be installed on the countertop or small rooftop by the domain. The architecture is also clearly designed as horizontally scalable: more sensing nodes can be configured, and when more ESP32 units are paired with the same Blynk project, with each node over a single growing zone. Vertical scaling - tracking a greater reservoir of a multi-rack NFT system, as with vertical scaling it can be recalibrated (without hardware redesign) by varying dosing volumes and threshold values.

The monitoring and control system is crop-neutral. Although configuration values in the Blynk console have been adjusted according to the lettuce in this study, the system can be configured to support basil, spinach, kale or even fruiting crops like cherry tomatoes. This adaptability renders the platform a good fit community gardens cultivating a broad array of produce.

In addition to the simple monitoring, data-logging of the system opens opportunities to integrate the system with machine-learning pipelines. The historical trajectories of EC and DO, which relate to growth photos of the plant, taken at time points, could be used to train a regression model that was able to predict harvest date or even see the presence of early nutrient stress, even before it was visible with the naked eye. This type of analytics at scale would be possible with cloud interconnection with services like AWS IoT or Google Cloud IoT Core.

The long-term ambition is to have a full-farm management system where several growing facilities hydroponics, aeroponics, and container soil gardens are controlled by a single dashboard where nutrient scheduling, consumable ordering, and energy management control are all automated to maximize grow-light electricity use during off-peak tariff periods.

XI. FEASIBILITY ANALYSIS

Technical Feasibility:

Everything in this system at the hardware level is commercial, well documented and active open-source projects. The ESP32, DS18B20, EC probe, and BH1750 are typical components that are available in bulk with major electronics vendors across the world. The Blynk 2.0 project has a free tier that allows one farm deployment size, is effectively supported by an API, and mobile SDK. There is no specialized making or tooling necessary.

Operational Feasibility:

Blynk mobile interface does not need any technical expertise to operate it - growers can ensure they are connected to the dashboard and can communicate with the dashboard through the dashboard-based interface in the same manner as they can with any consumer app. The system will be self-managed at the usual conditions of functioning; growers are to accept the notifications and conduct the physical examination every week. The user with the basic knowledge of electronics only needs about two hours to set it up, since it is facilitated by step-by-step documentation.

Economic Feasibility:

The final cost of the prototype board of materials amounts to about USD 38 at retail values: ESP32 dev board (USD 5), DS18B20 probe (USD 3), DO sensor module (USD 12), EC probe (USD 7), BH1750 module (USD 2), relay board (USD 3), peristaltic pump (USD 4), and cab The Blynk free version includes monitoring up to one device. The increases of 30 40 percent in Lettuce yield compared to unmonitored hydroponic systems, as cited in similar experiments, indicate that the hardwares will pay the payback period of two to three growing cycles.

The legal and ethical practicality:

The system does not deal with personal financial information and gathers agronomic sensor measurements only. Definite IoT security measures on an HTTPS transport, token-based authentication, non-existent open ports are applied. The system is in line with the general data-protection requirements in data that is not personal and biased towards the environment and does not pose any regulatory issues within the Indian agricultural environment.

XII. REQUIRED TOOLS

- ESP32 Development Board (Espressif WROOM-32): Central board with inbuilt Wi-Fi, two core processor and enough GPIO to connect all the sensor and actuator.

- Arduino IDE 2.x: IDE to develop, compile and upload C/C++ code to the ESP32. Supported on ESP32 board support package and sensor libraries.
- DS18B20 Water Proof Temperature Sensor: Single-wire digital sensor that can be used directly in the nutrient reservoir, with an accuracy of ±0.5 C.
- Gravity Dissolved Oxygen Sensor (DFRobot): Analog sensor module with real-time DO readings in mg/L, with a saturation-curve compensation algorithm in the firmware.
- EC/TDS Probe: Conductivity probe to the 0-5 mS/cm range as would be found in hydroponic nutrient solution.
- BH1750 Ambient Light Sensor: Digital lux meter using I2C with a range of 1-65535 lux to check the functionality of grow-lamps as well as record the daily light integral.
- Relay Module (4-channel): Activates air pump, and peristaltic nutrient pump, as a reaction to DO and EC events.
- Blynk 2.0 Platform: Cloud IoT back-end offering data ingestion, storage, dashboard visualization and push-notification.
- Visual Studio Code (excluding PlatformIO): Another development environment that provides better code completion, library management, and debugging than the Arduino IDE.
- Wi-Fi Router / Mobile Hotspot: This can be used to either give the ESP32 access to a Wi-Fi Internet connection or provide mobile access to the Wi-Fi network.

XIII. FEATURES

- Monitoring of 4 parameters (DO, EC, temperature, light) with 30s refresh rates and five-point moving averages to remove sensor noise.
- Smartphone dashboard which can be accessed anywhere with internet connection and provides real-time readings in the form of color-coded status lights and 90-days history charts.
- Having automated trigger and push notifications that are based on sustained parameter violation with set thresholds and hysteresis to avoid alert fatigue.
- Closed-loop control with actuators: DO and EC control through automated and autonomous solutions between weekly inspections of solution quality control, i.e., DO-triggered aeration and EC-triggered nutrient dosing.

- Offline robustness: local as well as cloud connectivity Logic of control The logic of local control behaves in the absence of cloud connectivity, and reconnection triggers the queue and flushing of data packets.
- Modular, crop-agnostic design: threshold parameters can be set in the Blynk console without the need to reload the firmware.
- Native records with time stamping and can be used in retrospective analysis and later integration with machine-learning.
- The system is accessible to the hobbyists, in education facilities and small-scale city farmers, with low cost and an open-source firmware.

XIV. Proposed system Workflow.

Operation of the system commences on power-on, as the ESP32 makes its initialization programs, which establish the peripheral bus structure, initialize sensor driver programs and provide an early-profile connection with the local network using Wi-Fi. After connection, the firmware verifies itself with the Blynk cloud and retrieves the threshold that is currently set in virtual pins. The benefit of this design is that a grower can modify operating parameters, such as changing the setpoint of EC, as the grower passes through the seedling growth phase to the high-EC growth phase, simply by changing issue controls via the application will be reflected on the Blynk app, without any physical intervention on the hardware.

It is then the start of the main sensing loop. Raw readings are taken every 30 seconds when all the four sensors are used, averaged over the five previous readings, against the thresholds that are retrieved. The ESP32 also measures the status of any given parameter, whether or not it violated it in a 3 or more cycles, and makes the relevant action: activating or deactivating the air pump or nutrient dosing pump and sending the notification events to the Blynk server. Each all four current sensor values, together with the actuator state and a violation flag of each parameter are sent to the Blynk datastream.

The grower sees and interacts with a live dashboard on the Blynk real-time dashboard which lives on his smartphone. The notification will come within a few seconds of the breach of a threshold lasting 90 seconds. From the app, the grower can react in real-time accept the alert, or turn a pump on to flush the system or change the threshold settings, assuming that the breach is more of an intentional move in growing conditions than a fault.

The hydroponic physical structure is parallel. The nutrient solution is pumped constantly into the root zone by the submersible pump. The float valve also maintains the same volume of the solution as water evaporates or the plants use it up. The closed-loop construction implies that the dissolved nutrients are not lost to drainage and very little top-up volume is required in order to maintain the level in the reservoir during the week.

The grower analyzes Blynk historical charts at the end of every week to determine the progress made in the growth cycle.

is running as anticipated - EC intake rates, trends in DO, and temperature profiles are all indirect indicators of plant health and metabolic activity. This is a weekly review, that is based on data rather than the un-monitored and subjective assessments that define unmonitored hydroponic management.

XV. Description of Data set and the laboratory set ups.

A. Dataset Description

The data produced by this system would be in time-series format, which would be measured at 30 seconds at a full 6-week growth cycle of lettuce, where the seedlings will be transplanted after two weeks and the harvest. In each record, there will be a UTC time, the values of the four sensor parameters, one binary flag per actuator and one binary flag per threshold. During the six weeks experimentation, there were almost 120,960 individual records per sensor channel, and about 600,000 data points per sensor group.

Then the dataset was exported out of Blynk after harvesting and analyzed offline in CSV format. EC consumption rate was calculated by a linear curve fitting the daily mean EC data yielding a measure of nutrient uptake rate which was well correlated with harvest fresh-weight yield (r = 0.91). Events of DO violation were tabulated and tallied and related with the observed physical condition of the roots discolouring observed after that particular event during physical inspection. The temperature steps beyond 24o C, which generally occurs during the afternoon hours in the uninsulated rooftop test conditions, was related to noticeable decreases in the daily EC consumption, which is in line with the existing literature findings of metabolic deceleration in the case of mild heat stress.

B. Experimental Setup

The test was carried out on a roof terrace covered in Jaipur, Rajasthan, India, over the months of November and December, where the daytime temperatures are cool (20 to 28 C) and the skies are clear and suitable to complement the LED grow lights. The reservoir used in the hydroponic system was a 30-liter HDPE system with a floating raft measuring 0.6 m x 0.4 m with an area of six 5 cm net-cup. The seedlings of Butterhead lettuce (Lactuca sativa var. capitata) were transplanted to the cotyledon stage.

Dilution was done at the recommended concentration of lettuce to a commercially available two-part hydroponic concentrate to make the nutrient solution. Start EC was to be 1.4 mS/cm and left to drift with the automated dosing system keeping the level at 1.2 mS/cm or higher and the pH manually adjusted to 6.0-6.5 at each 1-week monitoring - pH automation was not incorporated in this prototype but has been listed as a priority in the next development cycle.

A 45 W full-spectrum LED panel was added at night and would turn on at full-flow during 16 hours/day on a timer, with the BH1750 sensor ensuring proper operation and recording the real light-on and light-off time. The experiment was carried through a 42 day period. Harvest of lettuce heads were weighed fresh and compared with controls of 6 plants that had been growing in the same structure but had not been monitored by equipment of any kind at all - they were handled by the usual twice-a-day manual inspection protocol that the growers were involved with in the study.

XVI. RESULT ANALYSIS

Performance Analysis

The automation system performed better than the control based on manual monitoring on each of the observed dimensions. The monitored group had a fresh-weight yield of 187g per plant and the control group had 141g per plant on average fresh-weight per plant which was 33 better than the monitored group. The sizes of the observed heads were also more homogenous in the monitored group, and the coefficient of variation was 8% compared to 19% in the control which indicated that a more stringent environmental control decreased the variability within the batch.

The monitored group spent an average of 3.2 minutes in violation of DO before automated aeration was able to rectify the situation. DO values under 5 mg/L were only observed in the control group at intervals of manual inspection: the median value of the time during which the sensor did not record data was approximated at 4.2 hours. At the fourth week of monitoring, one of the plants under the control group exhibited visible signs of Pythium disease, unlike the monitored group that did not reveal an incidence.

Monitoring group ingested 18.4 liters of water during the 42-day cycle and 24.1 liters of water during the control group 24% less than in the monitored group due to combination of the float-valve automation and the absence of over-dilution incidences which were evident during the control group when growers added water without looking at the existing volume of water.

Monitoring Dashboard (System Interface)

The Blynk dashboard was programmed with 6 widgets, which included a labeled gauge of each of the four sensor parameters, a historical line chart of the 24-hour trends of EC and DO, and an event log showing the last ten alert events this time with a timestamp. Feedback received in response to the questionnaire by both of the growers who were involved in managing the Monitored Group throughout the experiment expressed the same sentiment positively: both of them claimed that the Dashboard reduced their concern over leaving the installation unmonitored and that the notification system identified two actual anomalies (a leading pump jamming in week three and a grow-light failure in week five) that would otherwise have remained unnoticeable over the course.

XVII. Summary and outlook.

The hydroponic lettuce growth system outlined in this paper using the IoT, together with inexpensive, easily accessible hardware (an ESP32 microcontroller, four commodity sensors, a small relay module, and the Blynk cloud platform) show that even simple stateful methods such as monitoring crop production, resource consumption, and operational convenience can bring quantifiable and significant changes in crop yields, resource usage, and operational convenience when compared to unmonitored hydro

The 33 percent increase in the fresh-weight yield, as well as the 24 percent reduction of water-use, recorded after six weeks in the lettuce experiment, confirms the hypothesis of the core design: that ongoing, automated control of parameters coupled with closed-loop actuator control are good agronomic alternatives to the hypothetical advantageous benefits reported in earlier literature. The remote notification system illustrated its usefulness in identifying two actual equipment failures during the experiment - just the type of thing that leads to major loss of crops in unmonitored installations.

In the future, it is intended to improve in various ways. The first priority is to add auto-pH control, and to pair a peristaltic dosing pump, with pH-up and pH-down solution, to a digital pH probe, thus removing the final significant manual maintenance operation. Adding a camera module with a periodical canopy scan would allow tracking visual growth and later on, disease detection through AI with convolutional neural network models with training on labeled images of lettuce.

On the data-analytics side, time-series data produced by existing system gives a base to model the EC consumption rate as a predictor of days-to-harvest - which would make the dashboard show a dynamically changing number of days to harvest. The dataset would be stored in a long-term storage backend (AWS S3 or Google Cloud Storage) to be able to becloud-integrated and provide cross-seasonal analysis and comparison across multiple sites. Lastly, it is easy to expand the architecture to new growing modules NFT channels, aeroponic towers or soil-based container gardens, all of which report to the same Blynk project due to the modularity of the architecture. Integrated with renewable energy (a solar panel and battery system to charge the grow lights and sensors off-grid), the platform would be a fully operational and self-sufficient urban food production system that would not require significant infrastructure and commitment, but would still have a significant impact on local food security.

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