BioSense Pot (B.S.P)

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***Abstract* — This paper presents the Bio-Sense Pot, a self-regulating smart plant system designed for hobbyist use. It integrates adaptive lighting, automated irrigation, and environmental monitoring using a modular ESP32 architecture. The system leverages dual spectrometers and light intensity sensors, and moisture/temperature sensors to create an optimized environment for plant growth. Light sensors were calibrated with lab sensors. Testing results demonstrate reliable sensor performance and system responsiveness. The Biosense Pot aims to reduce human error in plant care and provide remote monitoring through a web interface.**

***Index Terms* — Smart agriculture, automated irrigation, environmental monitoring, ESP32, soil moisture sensor, spectral sensor, I2C multiplexer, LED grow light, smart plant system, IoT plant monitoring**

I. Introduction

Taking care of indoor plants can be difficult, especially when it comes to maintaining consistent watering and lighting schedules. Many commercially available smart pots offer basic automation but lack real adaptability based on changing conditions. The Biosense Pot was developed to address this limitation by creating a self-regulating system that actively monitors its environment and makes real-time decisions based on sensor feedback.

By integrating adaptive growth lighting, soil moisture sensing, and environmental data collection into a single ESP32-based platform, the Biosense Pot aims to reduce human error in plant care while offering a hands-off experience for users. The system combines multiple sensing technologies, including light intensity sensors, multispectral analysis, and soil/environmental monitoring, to dynamically adjust lighting and irrigation. With built-in Wi-Fi capabilities, the pot also supports future expansion for remote monitoring and control through a web interface, making it a practical solution for both hobbyists and future scalable applications in automated agriculture.

II. System Architecture

The Bio-Sense Pot is built around an ESP32 microcontroller, which manages all data collection and control operations. Its sensor suite includes two TSL2591 light intensity sensors and two AS7341 spectral sensors for dynamic lighting analysis, a DHT11 for ambient temperature and humidity monitoring, and dual soil moisture sensors for precision irrigation control. A 5V ultrasonic sensor tracks water reservoir levels. A submersible 5V water pump delivers irrigation as needed. The WS2812B LED grow light strip, also powered at 5V, provides customizable spectral output for plant development. Light collection is ensured by Power delivery is handled by a dual-voltage supply system: 5V lines power the LED strip, ultrasonic sensor, and pump, while 3.3V lines support the ESP32, light sensors, and soil moisture probes.

III. Key Feature Components

In order to gain a better understanding of how our automated plant-care system works, it is helpful to think of it as an ensemble of modular hardware subsystems, each of which is responsible for one aspect of monitoring or control. As we go through the system, we will explain each major component, its role, and how it interfaces with the rest of the system in detail.

Microcontroller

Our entire system relies on the ESP32, which is a dual-core 240 MHz microcontroller that includes Wi-Fi and Bluetooth functionality that is integrated into the board. Each read-and-write cycle is orchestrated by the software. In order to avoid I2C address conflicts, it toggles power-gates for individual sensors, reads analog and digital signals (soil probes, ultrasonic echo, and DHT11), executes moisture-based pump logic, and drives NeoPixel grow light strips over a single data line. It has abundant GPIOs and ADC channels, so that the entire plant-care loop runs smoothly and can later be extended for remote monitoring over Wi-Fi using the built-in WI-FI module.

Ultrasonic Water-Level Sensor (HC-SR04)

In order to measure the depth of a reservoir, this waterproof probe sends a trigger pulse that lasts for 10 milliseconds and times the echo response that follows [1]. This, mounted above the tank, reports the distance to the surface of the water (in centimeters), which we then clamp between the known "empty" (13.7 cm) and "full" (1.9 cm) heights of the tank. By calculating a fill percentage over the span of that time period, we can allow the system to detect low-water conditions before the pump runs out of water.

Temperature & Humidity Sensor (DHT11)
In the DHT11, the ambient temperature and relative humidity are provided over a single data line shared by all the devices (GPIO 14). Despite its modest accuracy (only 1 degree Celsius and 5% relative humidity), this system reliably flags environmental extremes and can be used in the future to feed automatically into adaptive lighting schedules or ventilation control systems [2].

Soil-Moisture Subsystem
We employ two probes:

- The primary irrigation controller we use is the **capacitive sensor** (ADC 34)**.** Using its polymer plate, the instrument measures dielectric changes in moist soil. Raw counts are mapped to the range of 0–100% moisture and the pump is turned on when the moisture falls below 30%, and it is turned off when it reaches 70%.

- **Resistive Sensor (ADC 32)** provides a secondary "display-only" water level reading. Although prone to corrosion, it offers a simple cross-check for the ultrasonic measurement without influencing pump decisions.This approach ensures accurate measurements without interference. By alternating between the sensors, we maintain efficient use of resources while providing reliable stable water level measurement.

Broadband Light Sensors (TSL2591)
Two TSL2591 digital light sensors are included to track light intensity. The internal sensor sits beneath the diffuser and verifies light delivered to the plant, while the external sensor measures ambient sunlight. Both communicate via I²C and support variable gain and integration time, enabling accurate detection across a wide dynamic range. These sensors are essential for Lux-to-PPFD conversions and allow the system to adjust LED output when ambient light is sufficient [3]. As a result of the sensors sharing the same I2C address, each sensor's 3.3 V supply is governed by a GPIO pin on the ESP32 (pins 25 and 33). At any given time, the firmware alternates between powering one sensor at a time, initializing it, reading the lux value, and then powering it down, ensuring that they can co-exist on the same bus without conflicting with each other.

Multispectral Sensor (AS7341)
In order to improve color profiling, the AS7341 10-channel spectral sensors monitor light composition across visible and near-IR bands. One sensor is mounted internally to measure grow light output below the diffuser, and the second externally to detect ambient spectral content. These sensors enable real-time feedback on red-blue spectral balance, allowing dynamic adjustment of LED settings based on target ratio thresholds. Spectral readings were calibrated against a reference spectrometer to ensure accurate tracking [4]. are used for capturing the intensity of blue (445nm), green (555nm), and red (680 nm) channels. The PCA9548A I2C multiplexer is used to route both of these I2C devices behind a single I2C address as they share an I2C address. The ESP32 can read a single sensor at a time, or it can read a number of sensors in succession, allowing the real-time spectral feedback to be used for adjusting the grow lights output or diagnosing the health of a plant.

Grow-Light Source (BTF Lighting Strip)
Our Grow lights are designed with 114 WS2812B LEDs that are arranged in an array above the plant. A single data pin is used to control this strip, which displays an alternating red, blue, and white pattern to optimize the effectiveness of photosynthetic processes [5]. A diffuser was mounted beneath the strip to ensure even light distribution across the canopy and reduce spectral hotspots. The grow light operates dynamically in response to both internal and external sensor feedback, adjusting brightness and red-blue ratios to meet PPFD and spectral balance targets . There is a setting in the firmware for adjusting the brightness, and future versions may be able to develop dynamic day/night cycles, as well as bloom modes that can be triggered by the user.

I²C Bus & Power Management
There are two main I2C lines (SDA 21 and SCL 22) that are shared by all digital sensors. The sensors (TSL2591 or AS7341) are either power-gated via an N-MOSFET on their VIN line or they are isolated behind the I2C multiplexer in order to prevent address clashes and reduce idle current (PCA9548A reset/OE on GPIO 16) to avoid address collisions and to minimize idle current.

IV. System Concepts

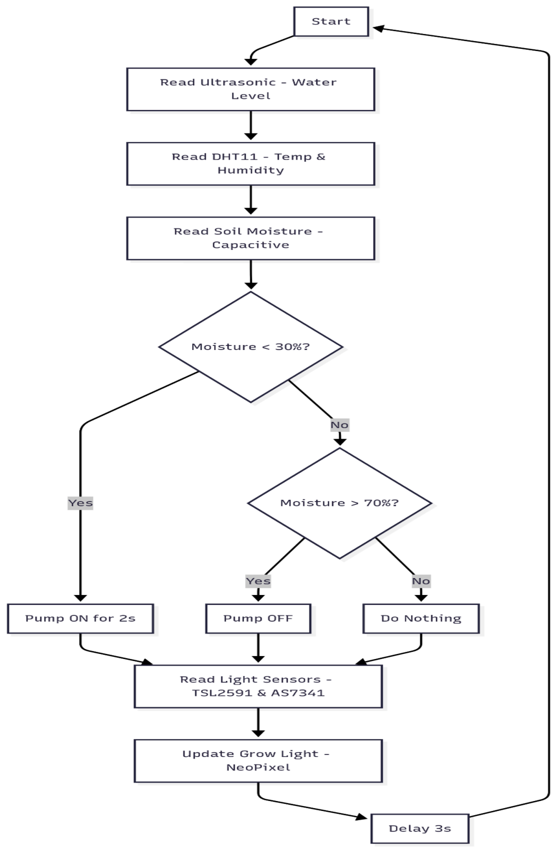


Fig. 1 Watering system flow chart

Control Cycle (Sense → Decide/Act → Wait)

During every 3 second loop, the microcontroller begins by entering Sense mode, in which it sequentially polls:

1. **Ultrasonic Water‑Level** measures echo time to compute tank fill % (1.9 cm full → 11.7 cm empty).

2. **DHT11** reads ambient temperature (°F) and relative humidity (%).

3. **Capacitive Soil Moisture** returns 0–100 % moisture level.

As a result, these fast measurements are taken throughout the entire startup and steady state cycles (the total duration is only 50 milliseconds) without taking any action.

The system automatically enters Decide/Act mode as soon as it enters Decide/Act:

- **Irrigation**—if soil < 30 %, pump ON for 2 s; if soil > 70 % and pump was ON, turn it OFF; otherwise leave pump unchanged.
- **Grow‑Light Update**—refreshes the LED strip with the chosen red/blue pattern.

It should be noted that each irrigation burst has a limit of two seconds and the lighting updates take only milliseconds, so Act takes only a few seconds to complete. Finally, the controller enters the Wait state, which is a 3 s delay which involves the following:

- Requires the soil to settle for a period of time before the next moisture reading,

- Assures that sensor polling is limited and that LEDs do not flicker.

Sense is notified at the end of the process and control is looped back. By implementing a fixed DDW -Sense→Decide/Act→Wait cycle that has no asynchronous interruptions whatsoever - there is a constant, predictable and continuous monitoring and control of the water level, climate, soil moisture, and lighting. Routing ensures that the system operates efficiently without compromising the reliability of sensitive components. This design approach not only enhances system responsiveness but also extends the overall lifespan of the system by preventing potential damage caused by power fluctuations or overloads.

V. Optical System Design and Testing

Our goal was to develop an adaptive lighting system that could dynamically adjust its output in response to both internal measurements beneath the diffuser and external ambient conditions. The red-to-blue light ratio plays a critical role in regulating photosynthesis, stem elongation, and leaf expansion across various growth stages [6]. Equally important is ensuring that the light intensity, measured in photosynthetic photon flux density (PPFD), meets the minimum threshold required for sustained growth. By incorporating spectrally and intensity-sensitive sensors into a closed feedback loop, we aimed to ensure that the system could meet set light intensity thresholds while preserving red-blue spectral balance. This required not only accurate data collection, but also a system capable of interpreting and acting on that data in real time. The resulting system modifies brightness and color output automatically, increasing or reducing light as needed to maintain target intensity levels and spectral ratios based on real-time measurements.

Optical System Layout
The optical system is divided into four subsystems: internal light intensity sensing, internal spectral sensing, external light intensity sensing, and external spectral sensing. The internal systems are mounted beneath the diffuser and angled upward toward the grow light. Their purpose is to directly measure the light output from the LED array in order to verify intensity and spectral composition. This allows the system to make accurate, real-time adjustments to maintain the intended lighting conditions at the plant canopy. The external systems are positioned on the outer edges of the housing and point outward to capture ambient light data from the environment. These measurements allow the system to account for natural light entering the pot and reduce LED output when external conditions compliment internal conditions sufficiently. All four subsystems are secured inside custom 3D-printed housings integrated into the structural beams, each fitted with reflective light funnels to improve light collection onto very small sensor spaces. Sensor readings are relayed over a shared I^2C bus to the ESP32 for processing and control.

Optical Simulations and Physical Testing
Initial system layout and alignment were modeled in Ansys Zemax OpticStudio using sequential ray tracing. This allowed us to simulate light paths from the LED array to each sensor, accounting for diffuser effects, housing geometry, and angular field of view. Both the internal and external optical subsystems were modeled independently, with emphasis on verifying that rays could reach the ~0.5 mm square sensor area after passing through the intended optical path. Reflective light funnels were tested virtually to confirm that rays entering from a wide range of angles could be redirected onto the sensor face with minimal loss. Final designs were exported and matched to 3D-printed components used in the prototype.

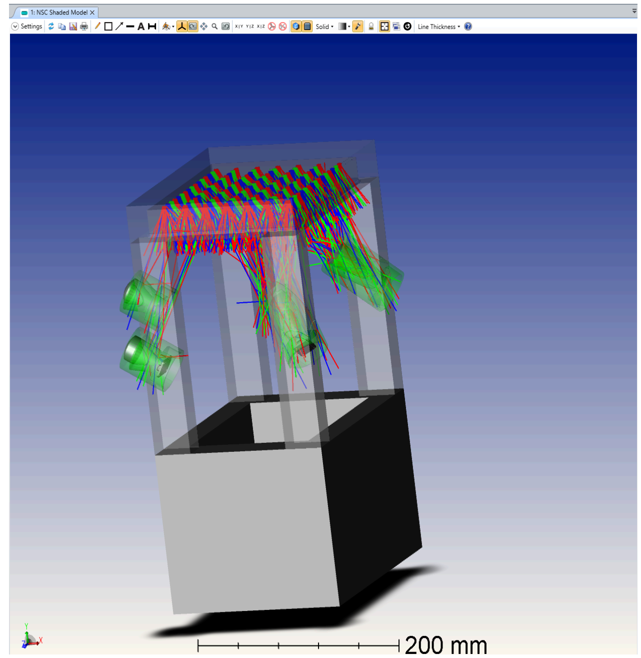


Fig. 2 Image of the central pot, lighting system, and optical systems modeled in Zemax

Physical testing involved exposing each sensor to controlled lighting scenarios and verifying that measured outputs aligned with simulated expectations. For the internal systems, multiple LED blends were applied at fixed distances to test intensity and spectral accuracy. For the external systems, ambient lighting was simulated using a fiber-based light source and measured under varying orientation conditions. These tests confirmed that both internal and external optical paths reliably transmitted light to their respective sensors and supported the intended feedback loop behavior in the complete system, after calibration and conversion was completed.

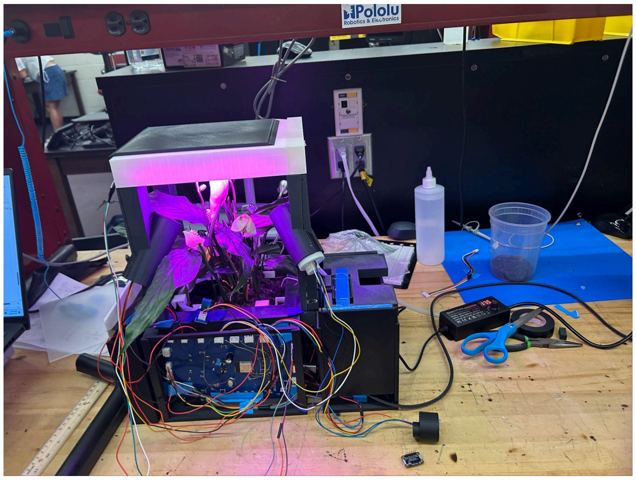


Fig. 3 Image of internal lighting testing occurring with BSP prototype

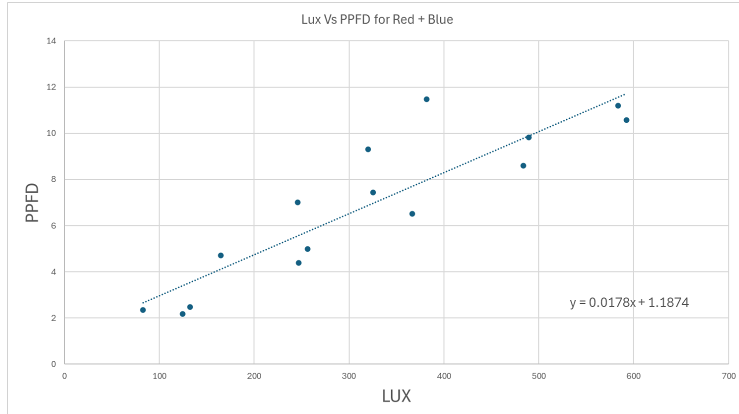


Fig. 4 LUX to PPFD conversion graph for internal system Red + Blue input light

Optical Sensor Calibration and Unit Conversion

To ensure accurate light regulation, both the intensity and spectral sensors were calibrated against reference equipment under controlled lighting conditions. The internal TSL2591 sensor was tested using known red-blue and red-blue-white LED blends at multiple brightness levels. Lux readings were recorded and compared to PPFD measurements collected with a Newport 918D-SL calibrated power meter placed at the same location and angle. These data were used to generate conversion curves from Lux to PPFD for each lighting condition. Although red-blue blends showed consistent correlation, the inclusion of white light introduced greater variance, requiring the use of condition-specific conversion models.

The AS7341 spectral sensor was calibrated by comparing its red-blue output ratios to those measured by a SpectraWiz reference spectrometer under identical lighting conditions. Each test used a fixed blend of LED output to generate a frozen SpectraWiz spectrum, which served as a behavioral baseline. Corresponding AS7341 readings were then collected and mapped onto this baseline to define the expected behavior of each spectral channel. This process allowed for direct comparison and compensation, ensuring that AS7341 measurements aligned with those of the calibrated system. The behavior mapping generated from these tests enables the ESP32 to monitor and correct the spectral composition of the grow light in real time.

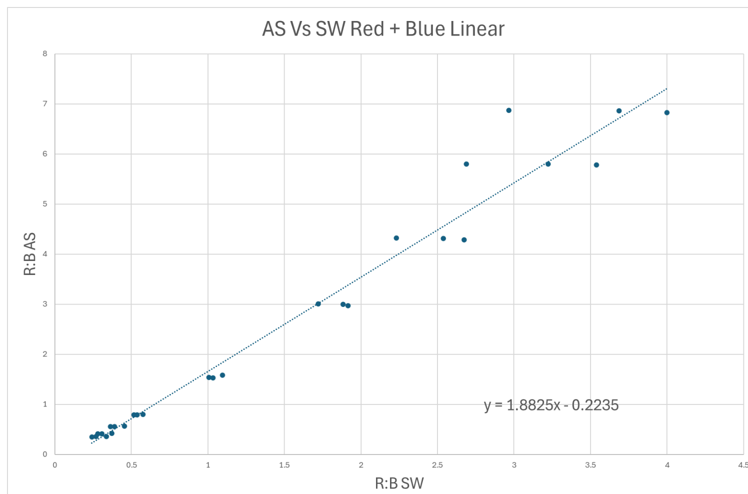


Fig. 5 Behavioral mapping of SpectraWiz Spectrometer onto internal AS sensor for Red + Blue light

Dynamic Lighting Process

Sensor data collected from the internal and external subsystems is processed by the ESP32 microcontroller to determine whether adjustments to the grow light are necessary. The internal intensity sensor confirms whether PPFD at the plant's level meets the defined target, while the internal spectral sensor verifies the red-blue ratio remains within tolerance. If ambient light measured by the external sensors contributes sufficient additional intensity, the system reduces LED output accordingly to conserve energy. Conversely, when ambient levels fall below the target range, the system increases intensity and adjusts the spectral output to maintain proper ratios. These adjustments are executed through software-controlled lighting output changes to the LED strip, allowing for continuous modulation of brightness and color balance throughout the day [7].

Limitations and Future Improvements

Although the system was successful in capturing usable light and spectral data, several limitations remain. Internal measurements are dependent on consistent diffuser transmission, which can vary slightly due to imperfections in material or positioning during assembly. The external optical systems are also limited by their fixed orientation, which may not capture the full range of ambient lighting conditions under indirect sunlight, or light coming in on a side that the external sensors cannot capture. In addition, the AS7341 spectral sensor, while effective after calibration, has limited effectiveness when we approach steeper red/blue ratios such as 5 to 1.

Future work will focus on refining the calibration curves using more extensive datasets and verifying sensor behavior under a wider range of lighting environments. Additional validation will also be performed to evaluate the system's stability over time and its sensitivity to minor spectral or intensity deviations. These improvements aim to improve accuracy in sensor readings and ensure that lighting adjustments remain true to the light being experienced by the plant.

VI. Power System Design and Implement

The Bio-Sense Pot employs a robust dual-channel power architecture built to support both low-power digital control and high-power actuation. The system is powered by four 3.7V 9900mAh lithium-ion batteries arranged into two series-connected pairs. One pair feeds a 5V step-down (buck) voltage regulator, and the second pair supplies a dedicated 3.3V regulator. This separation between logic and actuator power domains reduces noise interference and ensures the ESP32 microcontroller and sensors remain stable during load transients from high-current peripherals like pumps and lighting.

The 3.3V regulator exclusively powers the ESP32-WROOM microcontroller and all sensitive I2C-connected sensors, including the two TSL2591 light intensity sensors and two AS7341 spectral sensors. These components require high signal fidelity and tightly regulated voltage to maintain accuracy. A clean, independent 3.3V rail ensures consistent sensor operation, even during polling or concurrent communication over the I2C bus, which is critical for data reliability and system responsiveness.

The 5V subsystem drives all power-intensive peripherals: the submersible water pump, ultrasonic water level sensor, DHT11 temperature/humidity sensor, two capacitive soil moisture sensors, and the full-spectrum LED grow light system. The grow light comprises 114 WS2812B LEDs with a total current draw below 2A at maximum brightness. To prevent overloading the battery during lighting cycles, the LED strip is powered through a separate 5V regulator connected to a wall-supplied adapter. This hybrid supply strategy enables the system to run autonomously on battery for sensing and control, while drawing from the wall only during peak power demands.

All voltage regulators used in the system are rated for up to 25V input, allowing safe operation under the maximum expected input voltage (~8.4V from a fully charged 2S Li-ion configuration). By isolating high-draw peripherals from precision sensing elements and using appropriate power routing, the Biosense Pot maintains electrical stability, minimizes power loss, and provides modular scalability for future expansions or feature upgrades.

VII. Water-Pump Testing

By adding a fine stainless‑steel mesh and a 3D design at the pump inlet to block soil particles, we ensured reliable flow during our moisture and water‑level tests. In an initial run, the capacitive sensor fell from 60 % to 10 % (dry threshold), triggering a 2 s watering pulse that raised moisture to 83 %. As soil dried back to 25 %, a second 2 s pulse restored it to 75 %. Simultaneously, the ultrasonic sensor prevented dry‑running by inhibiting the pump when reservoir level fell to 10.7 % and re‑enabling it once refilled to 80 %. In steady‑state, moisture hovered around 50 % within our 30–70 % hysteresis—so no watering was needed, demonstrating that the mesh-filtered pump, capacitive threshold logic, and ultrasonic safety interlock work together to maintain optimal soil moisture without clogging or dry‑run damage.

VIII. Software Design

The control system of the Bio-Sense Pot runs entirely on an ESP32-WROOM microcontroller, which executes a consistent loop cycle broken into three main states: Sense, Decide/Act, and Wait. During the Sense phase, the ESP32 polls all relevant sensors in succession, including the ultrasonic water-level sensor, capacitive soil moisture sensor, DHT11 temperature and humidity sensor, as well as the TSL2591 and AS7341 light sensors. To avoid I2C address conflicts, the code toggles the power to each sensor using GPIO-controlled VIN gates or routes them through an I2C multiplexer. By handling one sensor at a time and ensuring it is fully powered down before moving to the next, the system avoids bus contention while also reducing idle current draw. Each sensor reading is non-blocking and designed to complete within a few milliseconds, allowing the system to keep a rapid loop cycle of 3 seconds. The Decide/Act phase follows immediately and determines whether the pump should be activated or if lighting adjustments are needed. Lastly, a 3-second Wait phase ensures system stability and reduces wear on components.

The Bio-Sense Pot sends data to the cloud using Wi-Fi, which is handled by the ESP32's internal networking stack. Every few seconds, a non-blocking HTTP POST request is sent to a Firebase Cloud Function. The payload contains all relevant sensor readings packaged into a JSON object. The firmware ensures connection reliability by checking Wi-Fi status before every transmission and retrying failed requests after a short delay. To keep the firmware responsive, the HTTP function is placed in its own FreeRTOS task separate from the sensor reading task. This prevents blocking during long transmission times and ensures that the control loop remains uninterrupted. Firebase was chosen because it integrates well with ESP32 and offers seamless real-time updates to a web interface built for the project.

In addition to basic monitoring, the web app also features integrated plant identification using the Plant.ID API. Users can upload a photo of their plant, which is then analyzed by the API to identify the species. Once the species is identified, a secondary request is made to OpenAI's API to retrieve relevant facts about the plant, including its optimal PPFD range, ideal soil moisture percentage, preferred temperature, and humidity conditions. These ideal environmental values are then displayed on the screen next to the current sensor readings, allowing users to compare real-time conditions against the target ranges. Furthermore, these optimal values are also sent back to the ESP32, which uses them to adapt its watering and lighting behavior automatically. This closed-loop feedback system provides personalized care routines for each plant, enhancing the effectiveness of the Bio-Sense Pot and demonstrating the potential for smart automation with AI integration.

VIV. Engineer Specification and Outcome

As Our engineering specifications are designed to ensure a reliable, responsive, and efficient automated plant care system, integrating soil moisture, lighting, and environmental monitoring capabilities. These specifications are guided by the core goals of timely reaction, data accuracy, and intelligent automation for optimal plant health.

The Soil Moisture Sensor response time is under 5 seconds, ensuring the system reacts rapidly to moisture changes. Water pump will be controlled by soil moisture threshold min and max percentage to switch on and off less than 5 second response time, the irrigation is precise and responsive to live soil readings. Similarly, the humidity and temperature sensors maintain an accuracy range 80-95%, suitable for general environmental awareness and correction. These parameters allow the system to maintain a consistent and healthy environment for plant growth.

On the lighting front, the Grow Light Output Spectral Ratios and Intensity Thresholds are finely tuned to match specific growth stages of plants, seedling, vegetative, and flowering, with red:blue light ratios of 1:2, 4:1, and 5:1 respectively, within a margin of ±0.1. The PPFD (Photosynthetic Photon Flux Density) is maintained at 60–85 $\mu mol/m^2/s$ for the Peace Lily, ensuring proper photosynthetic activity. Supporting this, the Spectrometer Response Time is less than 5 seconds, enabling dynamic adjustments, while the Light Intensity Control Resolution of 5–10 $\mu mol/m^2/s$ allows for fine control of light levels.

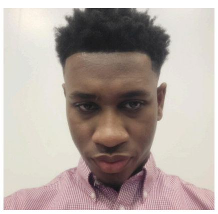
From a usability standpoint, the system supports remote app or website response within 10 seconds, ensuring timely visibility and control for users. System uptime is expected to remain between 80% to 90%, reflecting high reliability with minimal downtime. Collectively, these specifications form a robust framework that combines responsive automation, accurate sensing, and user-friendly interaction, optimizing the plant growth environment across all monitored parameters.

X. Conclusion

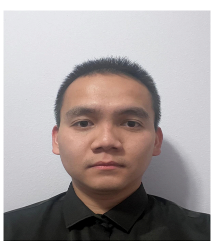
The Bio-Sense Pot demonstrates an effective and low-cost smart plant care solution that combines real-time sensor feedback, adaptive control, and modular design. With integrated lighting, irrigation, and environmental monitoring, the system maintains a consistent plant growth environment with minimal human input. Our approach to sensor integration, power management, and I^2C communication ensures both reliability and expandability. The use of dual spectrometers, moisture sensors, and ultrasonic water-level detection allowed for responsive control logic that performed well during testing.

This project highlights the potential for combining embedded systems with practical applications in smart agriculture. While the current version met our goals for automated plant care, future improvements could include predictive watering logic, more advanced mobile integration, and AI-based decision-making for adaptive plant growth strategies. Overall, the Biosense Pot serves as a strong foundation for continued development in automated environmental systems.

The Engineers



Brucely Charles is a 24-year-old graduating Electrical Engineering student who has applied to many jobs all over. Currently in the Marine Corps and have learned many disciplines.



Phuong Le is a 25-year-old Electrical Engineer who worked as an electrician for the military and decided to follow two uncles who are engineers in the family.

Ryan McDonnell is a 23-year-old photonic engineer who hopes to work on the simulation and design of electrical-to-optical connections.

Alex Beaufort is a 21-year-old computer engineer who plans to further his career in the automation industry.

by advisors Dr. Wei (ECE), Dr. Weeks and Dr. Kar (CREOL), and reviewed by Dr. Sonali Das, Mr. Mike McKee, and Dr. Xin Xin at the University of Central Florida.

References

[1] A. Kundu, M. Banerjee, and S. Mondal, "Water level measurement and monitoring system using ultrasonic sensor with error compensation," *2018 IEEE Applied Signal Processing Conference (ASPCON)*, pp. 29–33, Dec. 2018.

[2] A. K. Singh and A. K. Jaiswal, "IOT based smart environment monitoring using Arduino and DHT11 sensor," *2018 International Conference on Computation of Power, Energy Information and Communication (ICCPEIC)*, pp. 560–565, Mar. 2018.

[3] L. C. Pinho, "Adafruit TSL2591 High Dynamic Range Digital Light Sensor," *Adafruit*, 2023.

[4] ams OSRAM Group, "AS7341: 11-Channel Spectral Color Sensor," *ams OSRAM Datasheet*, 2023.

[5] R. J. D. Trouwborst, R. A. Voogt, and L. F. M. Marcelis, "Optimal red:blue light ratio for plant growth and development in controlled environments," *Acta Horticulturae*, vol. 956, pp. 183–190, 2012.

[6] H. I. Lee, Y. H. Kim, and D. E. Kim, "Analysis of spectral light intensity of high pressure sodium and metal halide lamps for plant growth," *Journal of Biosystems Engineering*, vol. 35, no. 6, pp. 413–420, Dec. 2010.

[7] L. Li, Y. Liu, Z. Liu, and M. Li, "An intelligent LED plant lighting system based on spectral compensation," *2018 Chinese Control and Decision Conference (CCDC)*, pp. 5877–5882, June 2018.