

UCF Senior Design 1

Bio-Sense Pot: Automated Hobbyist Plant Pot With Dynamic Lighting

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Chapter 1: Executive Summary.....	1
Chapter 2: Project Description.....	1
2.1 Motivations and Background.....	2
2.2 Goals.....	2
2.2.1 Basic Goals.....	3
2.2.2 Advanced Goals.....	3
2.2.3 Stretched Goals.....	4
2.3 Objectives.....	5
2.3.1 Basic Objectives.....	5
2.3.2 Advanced Objectives.....	6
2.3.3 Stretch Objectives.....	8
2.4 Features and Functionalities.....	8
2.4.1 Environmental Monitoring.....	9
2.4.2 Power management System.....	9
2.4.3 Light Diffuser.....	9
2.4.4 Adaptive Lighting and Irrigation.....	9
2.4.5 Spectral Analysis.....	10
2.4.6 Remote Monitoring and User Interface *.....	10
2.4.7 Plant identification and AI Assistant *.....	10
2.4.8 LCD Dome *.....	10
2.5 Diagrams.....	10
2.5.1 Hardware Block Diagram.....	11
2.5.2 Flow Charts.....	12
2.5.3 Optical Design Diagram.....	16
2.6 Requirements and Specifications.....	17
2.6.1 Requirement Specification:.....	17
2.6.2 Marketing Requirements.....	21
2.7 House of Quality.....	21
Chapter 3: Research and technologies comparison.....	24
3.0 Existing optical laser detection plant.....	24
3.1 Research.....	25
3.1.1 Existing technologies.....	25
3.1.2 Research Result.....	27
3.1.3 Part Selection.....	27
3.2 Temperature Sensor.....	28
3.2.1 Thermocouples.....	28
3.2.2 RDT resistance temperature detector.....	28
3.2.3 Semiconductor Temperature Sensor.....	29
3.2.1 Part Selection.....	31
3.3 The Technologies for soil moisture.....	33
3.3.1 Capacitance sensors.....	33

3.3.2 Time Domain Reflectometry.....	33
3.3.3 Resistive (conductive) sensors.....	34
3.3.4 Tensiometers.....	34
3.3.5 Part Selection.....	35
3.4 Types of Solar technologies.....	37
3.4.1 Monocrystalline.....	38
3.4.2 Polycrystalline solar panels.....	38
3.4.3 Thin Film solar panels.....	38
3.4.4 Concentrated Solar power.....	39
3.4.5 Part Selection.....	40
3.4.6 Upper-Pot Support Stand.....	43
3.5 Auto watering system.....	46
3.5.1 Water pump type.....	46
3.5.1.1 Submersible Water Pump.....	46
3.5.1.2 External Water Pump.....	46
Water pump type features comparison table.....	47
3.5.2 Water pump Selection.....	47
3.5.3 Water Level Sensor.....	49
3.5.3.1 Capacitive Water Level Sensor – DFRobot Capacitive Sensor.....	49
3.5.3.2 Resistive Water Level Sensor – DFRobot Gravity Analog Water Sensor.....	50
3.5.3.3 Float Switch Sensor – DEVMO Mini Indicator Vertical Water Level Sensor..	50
3.5.3.4 Ultrasonic Water Level Sensor – DFRobot URM09.....	51
Water level sensor comparison table.....	51
3.5.4 Water level sensor selection.....	52
3.6 Batteries.....	53
3.6.1 Lithium-ion (Li-on) batteries.....	53
3.6.2 Lithium Cobalt Oxide (LCo) Batteries.....	53
3.6.3 Nickel Cadmium (Ni-Cd) Batteries:.....	53
3.6.4 Lithium Polymer (Li-Po) Batteries.....	54
Battery Comparison table.....	54
3.6.5 Battery Selection.....	55
3.7 Adaptive Spectral Lighting System.....	55
3.7.1 LED Grow Light.....	55
3.7.1.1 Design Requirements and Constraints.....	56
3.7.1.2 Types of Light Sources for Controlled Lighting.....	61
3.7.1.3 Component Evaluation and Selection.....	62
3.7.2 Light Intensity Sensors.....	65
3.7.2.1 Design Requirements and Constraints.....	65
3.7.2.2 Types of Light Sensors.....	67
3.7.2.3 Component Evaluation and Selection.....	69
3.7.3 Light Diffusers.....	71

3.7.3.1 Design Requirements and Constraints.....	72
3.7.3.2 Types of Diffusers.....	73
3.7.4 Spectrometers.....	75
3.7.4.1 Design Requirements and Constraints.....	75
3.7.4.2 Types of Spectrometers.....	76
3.7.4.3 Component Evaluation and Selection.....	79
3.7.5 LCD Dome.....	80
3.7.5.1 Design Requirements and Constraints.....	81
3.7.5.2 Types of LCD and Switchable Materials.....	82
3.8 Software.....	83
3.8.1 EasyEDA.....	83
3.8.2 MultiSim.....	83
3.8.3 LTSpice.....	84
3.8.4 Eagle Fusion 360.....	84
3.8.5 Software Comparison and Selection.....	84
3.9 Microcontroller Selections.....	85
3.9.1 Introduction.....	85
3.9.2 Microcontrollers.....	85
3.10 Wireless Communication & IoT Connectivity.....	88
3.10.1 Introduction.....	88
3.10.2 Wireless Connection Methods.....	88
3.10.3 Wireless Communication Protocol.....	89
3.11 Cloud and Database Selections.....	92
3.11.1 Introduction.....	92
3.11.2 Cloud vs Local Storage.....	92
3.11.3 Databases.....	93
3.12 Mobile and Web Development Selections.....	95
3.12.1 Introduction.....	95
3.12.2 Frameworks.....	95
3.13 AI Integration.....	97
3.13.1 Introduction.....	97
3.13.2 Plant Identification.....	97
3.13.2.1 Pre-trained API Services.....	100
3.13.3 AI Assistant.....	102
3.13.3.1 Pre-trained NLP Options.....	103
Chapter 4: Standards and Design Constraints.....	106
4.1 Standards.....	106
4.1.1 Sensors.....	107
4.1.1.1 Safety Standards.....	107
4.1.2 Electrical and Communication Standards.....	108
4.1.3 Energy and Environmental Efficiency.....	108

4.2 Design Constraints.....	109
4.2.1 Power Constraints.....	109
4.2.2 Economic/Budget Constraints.....	109
4.2.3 Structural, Heat, and Environmental Constraints.....	110
4.2.4 Light Sensor Constraints.....	111
4.2.5 Safety Constraints.....	111
4.2.6 Water Management and Leakage Control.....	111
4.2.7 Maintenance and Modularity Constraints.....	112
4.3 Optimizing with Power Supply Integration.....	112
4.3.1 Power Supply Implementation.....	113
4.4 Water Resistance and Waterproofing.....	113
4.4.1 Water Resistance.....	113
4.4.2 Waterproofing.....	114
4.4.3 IP Rating system.....	114
Chapter 5: Large Language Model Usage.....	116
5.1 AI overview.....	116
5.1.1 ChatGPT.....	116
5.1.2 Perplexity AI.....	117
5.2 AI utilize in project.....	117
Chapter 6: Hardware design.....	119
6.1.1 Overall schematic:.....	119
6.1.2 Microcontroller.....	119
6.1.3 Multiplexer.....	121
6.1.4 Step down (buck) regulators.....	122
6.1.5 Charging module.....	124
6.1.6 Summary about schematic and PCB.....	125
6.10 Optical Hardware Design.....	127
6.10.1 Internal Spectrometer and Light Intensity Subsystems.....	129
6.10.2 External Spectrometer and Light Intensity Subsystems.....	134
Chapter 7: Software Design.....	136
7.1 3D Modeling and Printing Workflow.....	136
7.2 Schematic and PCB Layout with EasyEDA.....	137
7.3 Software System Overview.....	137
7.4 Embedded Software Architecture.....	138
7.5 Sensor Integration and Data Processing.....	139
7.6 Lighting and Watering Control Logic.....	140
7.7 App Software Design.....	140
7.8 Communication Between Pot and App.....	141
7.9 UI and UX Design.....	142
7.10 Security and Data Privacy.....	143
Chapter 9: System Testing and Evaluation.....	144

9.1 Optoelectronics and Optical Systems Feasibility Study and Testing.....	144
9.1.1 LED Grow Light.....	145
9.1.2 Light Sensors.....	145
9.1.3 Light Diffusers.....	151
9.1.4 Spectrometers.....	151
9.1.5 LCD Dome.....	152
9.2 Automatic Watering System Testing and Evaluation.....	153
9.3 Power Supply Design and Testing.....	154
Chapter 10: Administrative Content.....	155
10.1 Work Distribution.....	155
10.2 Project Milestones.....	156
10.3 Budget and Funding Estimations.....	157
Appendix A:.....	158

Chapter 1: Executive Summary

The Bio-Sense Pot is a self-regulating smart plant system designed for consumer and hobbyist use, with a focus on automation, dynamic systems, energy efficiency, and the reduction of user error in home gardening. By integrating multiple sensing, lighting, and control subsystems into a single platform, the system aims to support healthy plant growth in both indoor and mixed-light environments without requiring constant user intervention. It is designed around a modular ESP32-based architecture and prioritizes scalability, cost-effectiveness, and ease of integration with hobbyist components.

The system combines adaptive lighting, automated watering, and environmental monitoring in one compact unit. Optical subsystems, including dual spectrometers, grow lights, and light intensity sensors, enable dynamic control of light intensity and spectral balance to suit changing ambient conditions and plant development stages. Additional components include a temperature sensor and soil moisture sensor, which provide the user with plant system information, and inform the automated watering system to prevent over or under watering. The pot also houses a battery management system, voltage regulators, and relay-controlled pumps, all coordinated through the central microcontroller to maintain stable, autonomous operation. The system also includes a solar panel that supplements the internal power system, providing further off-grid operation and improving energy efficiency in sunlit environments.

This report outlines the development and integration of the system's optical and electrical subsystems, including research-driven component selection, practical design constraints, and feasibility testing methods. While some features, such as the LCD dome for ambient light shielding, and plant growth AI predictions may remain stretch goals, the Bio-Sense Pot establishes a foundation and proof-of-concept for a fully automated, sensor-driven plant care platform targeted at modern hobbyist needs and consumer accessibility.

Chapter 2: Project Description

The development of the Bio-Sense Pot followed a design process structured to balance feasibility, commercial practicality, and user ease of access. This chapter outlines the process by which core design constraints were identified and translated into subsystem requirements across both hardware and software. Attention was given to aligning each system function selection with measurable plant health needs, power limitations, and microcontroller compatibility. Rather than following a fixed-stage approach, the design process remained intentionally open, allowing for continuous feedback between testing and implementation. This chapter also documents key design trade-offs and decision points for the system structure presented in the following sections.

2.1 Motivations and Background

Maintaining plant health requires a proper balance of lighting, watering, and various environmental conditions, but manual plant care is frequently inconsistent and inefficient. Neglect, improper watering, and excessive or middling light exposure are all common occurrences for plant owners. People aren't intending to harm or kill their plants, but lack of time or knowledge typically results in just that. Automated systems can eliminate most of the role that human error plays in plant death by monitoring and adjusting conditions in real-time, ensuring the plants receive effective and consistent care while regularly informing the user as to the plant's condition, allowing the plant to avoid the common determinants that result from human error. By reducing the need for constant human oversight, plant ownership becomes much more accessible and worthwhile.

While there are existing smart planters, most of the available solutions are static systems, relying on pre-set watering schedules or unchanging lighting conditions. These systems fail to adapt to changes that occur in real time. Our project focuses on automating plant care through adaptive lighting, automated irrigation, and environmental monitoring. The system uses a custom-built spectrometer to analyze ambient light spectra, dynamically adjusting the grow-light spectrum and intensity based on various real-time conditions and the life-stage of the plant. This spectral analysis ensures that the plant receives the appropriate light wavelengths to optimize growth while compensating for external lighting variations. Additionally, soil moisture sensors regulate automated watering, and environmental sensors track ambient temperature to ensure stability and inform the user of a necessary intervention.

Despite its high level of automation, the system is not entirely independent of user involvement. Users still need to provide necessary input, such as identifying a plant's species and growth stage, to accurately define the acceptable bounds of various variables that would affect the system. Additionally, the water reservoir must be refilled periodically, and while the system can mitigate excessive light exposure through the upper pot structure, there may be some instances where the user needs to manually reposition the plant to avoid direct sunlight. The addition of the spectrometers and light intensity sensors further enhanced adaptability by providing real-time analysis of environmental lighting, ensuring optimal lighting conditions even under changing ambient light sources. The overall goal of this project was to maximize plant health while minimizing user workload, and the subsequent impact of possible user mistakes, creating a system that responds to changing conditions and can operate independently for a longer period of time than other smart pots.

2.2 Goals

This section covers the overarching goals that guided development of the Bio-Sense Pot, dividing them into basic, advanced, and stretch categories. Each goal category reflects a different level of system complexity and was used to prioritize feature

implementation during the design process. Basic goals established the system's minimum viable functionality, advanced goals introduced adaptive control and refined sensing, and stretch goals outlined optional features to be pursued if resources permit.

2.2.1 Basic Goals

The system's basic goals center on delivering reliable environmental regulation, foundational automation, and consistent light delivery to support healthy plant growth under ordinary conditions. A light diffuser ensures even distribution of artificial lighting, reducing the occurrence of hotspots and promoting uniform canopy development. Environmental sensors continuously track temperature, light intensity, and soil moisture, enabling the system to detect and respond to adverse conditions such as heat spikes, low light exposure, or improper watering cycles. Real-time soil moisture monitoring directs an automated watering system, minimizing user input while preventing overwatering and drought. Integration of solar panels supports low-maintenance, long-term use by reducing reliance on external power. These goals collectively establish the core functionality needed for plant care.

1. **Light Diffuser for Even Light Distribution:** Implement a light diffusion system to ensure uniform light distribution over the plant canopy, reducing hotspots and ensuring balanced growth.
2. **Environmental Monitoring:** Develop a sensor-driven monitoring system that continuously tracks temperature, light intensity, and soil moisture to maintain optimal growing conditions.
 - a. **Temperature Monitoring:** Measure and regulate ambient temperature to prevent extreme fluctuations that could harm plant growth.
 - b. **Light Intensity Monitoring:** Detects incoming light intensity from both ambient and artificial sources to ensure lighting conditions are not over or under - saturated.
 - c. **Soil Moisture Monitoring:** Automate irrigation based on real-time moisture readings, preventing overwatering and drought stress.
3. **Automated Watering System:** Integrate soil moisture sensors to automate watering in real-time, minimizing user intervention while ensuring optimal plant health.

2.2.2 Advanced Goals

The advanced goals focus on adaptive lighting, real-time automation, and remote accessibility. The grow light system adjusts both intensity and red-blue spectral output based on ambient conditions and the plant's growth stage. Light sensors and spectrometers guide these changes, along with automatic watering adjustments. Custom optical systems collect ambient light for accurate sensing in compact spaces. A

laser-based plant ID system can help tailor care to specific species. Users can monitor and control the system remotely through an online interface, with alerts and manual override if needed.

1. **Automated Lighting System:** Integrate light sensors to automatically adjust lighting conditions in real-time, minimizing user intervention while ensuring optimal plant health.
2. **Variable/Adaptive Light Spectra:** Implement a spectral lighting control system that actively adjusts the red and blue light ratios and composition in the grow light output, based on the plant's growth stage and surrounding environment.
3. **Custom-Built Optical Systems for Ambient Light Analysis:** Design and integrate four custom light collection systems to guide light to the small spectrometer and light intensity sensor spaces.
4. **Plant Identification:** Develop a comprehensive plant identification system that accurately determines plants using laser-based optical technology, benefiting farmers, gardeners, and researchers.
5. **An Online Monitoring and Control System:** Develop a web or mobile interface that allows users to remotely access and monitor plant health data, receive alerts, and make adjustments as needed.

2.2.3 Stretched Goals

The stretch goals focus on additional features that can help further reduce user and system workload, and improve system intelligence. Predictive growth modeling can allow the system to anticipate watering and lighting needs based on past conditions. An AI assistant will help users interpret system data and make better care decisions. The LCD dome provides active protection against harsh sunlight by affecting the transmission of incoming ambient light in real time. While not required for the product's core functionality, these additions would make the system more flexible, responsive, and user-friendly.

1. **Growth Prediction:** Develop a predictive algorithm based on historical data and environmental conditions to determine the optimal timing of watering and lighting.
2. **LCD Dome for Light Shielding:** Integrate an LCD-based shielding mechanism to reduce excessive sunlight exposure and prevent photodamage to plants. The dome will dynamically adjust transparency based on external lighting conditions.
3. **AI-Powered Assistant for Monitoring Plant Health:** Establish an AI-powered assistant that provides insights, recommendations, and real-time data on plant health to users.

2.3 Objectives

This section outlines the specific technical objectives that support the project goals defined in the previous section. Each objective corresponds to a measurable engineering task or performance target, allowing the team to evaluate design progress based on tangible outcomes. Objectives were written to ensure clarity around system behavior, sensor performance, communication protocols, and physical constraints. These targets helped inform testing procedures, component selection, and the overall structure of the adaptive control logic throughout the design cycle.

2.3.1 Basic Objectives

The basic objectives focus on establishing simple functionality across all major components. Environmental sensors for temperature, light, and soil moisture must be properly calibrated to ensure accurate readings across varying conditions. The light sensors are also expected to resolve both internal and ambient light intensity readings. A real-time interface is implemented to convey the sensor data to the user in a clear and accessible way. Voltage compliance is prioritized early on to guarantee the system operates within safe and reliable power margins. Together, these objectives ensure that the system can reliably collect and display the information it's built to manage.

1. **Ensure Even Light Distribution with a Light Diffuser:**
 - a. Design a diffusion system to scatter incoming grow light evenly, preventing hotspots and ensuring uniform illumination over the plant canopy.
 - b. Select optical materials that maximize light distribution efficiency without significantly reducing light intensity.
 - c. Conduct light intensity mapping to verify uniformity across different plant placements.
2. **Monitor and Regulate Environmental Conditions (Temperature, Light Intensity, and Soil Moisture):**
 - a. **Temperature Monitoring:**
 - a. Implement temperature sensors to continuously track ambient conditions.
 - b. Develop an alert system that notifies users when temperature fluctuations exceed safe limits.
 - c. Store historical temperature data to analyze environmental trends and adjust system settings accordingly.
 - b. **Light Intensity Monitoring:**
 - a. Use light sensors to measure both ambient and artificial light levels in real-time.
 - b. Provide feedback control to adjust grow light intensity based on external lighting conditions.
 - c. Integrate sensor data with the LCD dome's adaptive shielding mechanism to prevent light oversaturation.
 - c. **Soil Moisture Monitoring:**

- a. Utilize moisture sensors to regulate automated watering based on real-time soil hydration levels.
- b. Develop moisture thresholds to ensure plants receive adequate water without overwatering.
- c. Implement a calibration system to adjust watering behavior based on different soil types and plant needs.

3. Automate Watering Based on Soil Moisture Readings:

- a. Link data soil moisture sensors to the onboard pump controller behavior to allow for proper watering of plant soil .
- b. Set moisture thresholds based on plant or species, that trigger watering cycles accordingly.
- c. Minimize user involvement until water refill is necessary.

2.3.2 Advanced Objectives

The advanced objectives define how adaptive lighting, real-time system control, and species-specific plant care are implemented. Sensors and spectrometers must be tested for accuracy, while lighting control systems must respond dynamically to both ambient input and plant growth stage. A compact optical system is required to deliver ambient light into constrained sensing areas. Plant identification enables tailored care based on species, and the remote monitoring interface allows users to access live data and make changes without being onsite. Together, these objectives support a high level of system autonomy with minimal user involvement.

1. Automate Watering and Lighting Adjustments Based on Real-Time Data:

- a. Develop a control algorithm that adjusts grow light intensity based on sensor feedback.
- b. Use real-time input from internal light sensors and spectrometers to track overall exposure.
- c. Maintain target lighting levels throughout daily and seasonal ambient fluctuations.

2. Implement an Adaptive Light Spectrum System:

- a. Use red and blue LED control channels to vary spectral output based on growth stage.
- b. Use collection lenses and internal reflective cones to maximize capture efficiency within small form factors.
- c. Match lighting output to plant needs while avoiding spectral oversaturation.

3. Integrate Custom Optical Systems for Light Collection

- a. Design four compact optical paths to direct ambient light to the spectrometer and intensity sensor.
- b. Use spectral measurements to optimize adaptive lighting adjustments beyond basic intensity control.

4. Develop a Plant Identification System for Customized Care:

- a. Utilize image processing in conjunction with existing databases and identification software to classify plant species and adjust system settings accordingly.
- b. Enable a manual identification mode, allowing users to select their plant type if automatic recognition is inconclusive.

5. Establish an Online Monitoring and Control System:

- a. Develop a mobile interface that allows users to view live sensor data, adjust settings, and receive notifications.
- b. Implement real-time alerts for critical conditions such as low water levels, extreme temperatures, or equipment failures.
- c. Enable remote system adjustments, allowing users to adjust watering, lighting, and shielding settings as needed.

2.3.3 Stretch Objectives

The stretch objectives aim to enhance the system's decision-making processes and reduce the need for manual oversight. By allowing the user to either photograph their plant, allowing the system an opportunity to identify it, or input plant species and preferences, the system can begin tailoring its behavior to match requirements specific to a type or category of plant. Firmware and control systems analyzed collected data to recommend or automatically apply changes to lighting and irrigation schedules. Features like the LCD dome will help the system respond to excessive sunlight, and the AI assistant may offer real-time feedback or suggestions. These objectives enable a smarter and more dynamic plant care experience.

1. Develop Predictive Growth Modeling for Smarter Automation:

- a. Data from historical plant health and environmental conditions can be used to train predictive algorithms. Using artificial intelligence, recommend the best watering and lighting schedule for your plants. Improve predictions continuously with adaptive learning.
- b. Train an adaptive growth model that refines watering and lighting schedules based on long-term trends.
- c. Integrate self-correcting automation, allowing the system to modify its behavior based on observed plant responses.

2. Develop an LCD Dome for Adaptive Light Shielding:

- a. Implement an LCD-based shielding mechanism that modulates transparency based on real-time light intensity data.
- b. Integrate light sensors to dynamically adjust the dome's opacity, preventing excess natural light from overwhelming the plant.
- c. Develop low-power operation logic to ensure minimal energy consumption while maintaining responsiveness.

3. Create an AI-Powered Plant Health Assistant:

- a. Create a chatbot based on collected data that provides real-time insights. Implement AI-driven plant care recommendations. Use a mobile app to facilitate interactive communication.
- b. Provide detailed growth insights and proactive alerts, helping users make informed decisions about their plants.

2.4 Features and Functionalities

This section outlines the key components that make up the Bio-Sense Pot system and describes how each contributes to overall functionality. Features such as adaptive lighting, spectral analysis, moisture sensing, and environmental monitoring are explained in conjunction with supporting elements such as power management, light diffusion, and user interface control. Together, these functionalities allow the system to respond dynamically to changing environmental conditions while reducing the need for manual plant care.

2.4.1 Environmental Monitoring

Our system integrates a network of sensors that monitor ambient environmental variables that can directly impact plant health. This includes: A water level sensor that detects hydration levels and triggers irrigation when needed, temperature sensors that alert the user to excessive fluctuations, and light sensors that measure both interior and ambient light intensity and spectra. These inputs provide the central data needed for proper control of the system, adjusting conditions automatically when values fall outside of previously defined thresholds.

2.4.2 Power management System

The Bio-Sense Pot includes an internal power management system that prioritizes energy efficiency and long-term autonomy. A solar panel supplements battery power, allowing for temporarily unrestricted placement of the pot during daytime. Components are designed to operate under low-power conditions when necessary, and the system will prioritize critical functions if the available power drops below a set threshold. This helps ensure the reliable operation of the pot over extended periods without intervention.

2.4.3 Light Diffuser

The light diffuser evenly distributes grow light output evenly across the plant space. Without a diffuser, artificial lighting can create hotspots, which may cause uneven

growth in the areas of low intensity or localized overheating in the areas of high intensity. By softening and spreading the emitted light, the diffuser reduces harsh shadows and ensures a consistent intensity across the plant's surface. This helps maintain stable and even plant growth regardless of its orientation or position within the pot.

2.4.4 Adaptive Lighting and Irrigation

The system's lighting and irrigation systems responded dynamically to the plant's environment. The LED 's light intensity and red/blue spectral composition are adjusted in real time based on data from light sensors and spectrometers. Watering was similarly handled through feedback from the soil moisture sensor, which only activates irrigation when the soil is below the plant's required hydration threshold. These systems reduce much of the need for manual scheduling and help prevent common issues that result from incorrect watering and lighting practices.

2.4.5 Spectral Analysis

An internal spectrometer analyzes internal light while an external spectrometer monitors ambient light to determine spectral composition. This allows the system to adjust the grow light spectrum in response to changes in external lighting. For example, if the surrounding environment lacks red or blue wavelengths, the grow light will compensate by increasing output in those bands. This level of control ensures that the plant consistently receives the ratio of red to blue light most important for that plant's growth stage, regardless of time of day or indoor vs. outdoor lighting conditions.

2.4.6 Remote Monitoring and User Interface *

A remote interface—either web or mobile—allows users to monitor the system in real time. Live sensor data is transmitted to the interface and displayed in a clear, readable format. Users receive notifications when conditions deviate from acceptable ranges and can make manual adjustments when needed. While the system is built to be largely autonomous, this interface ensures the user stays informed and maintains control over important parameters.

2.4.7 Plant identification and AI Assistant *

A plant identification system helps define the correct lighting and hydration needs based on species and growth stage. Over time, the system can track environmental and sensor trends to predict growth patterns or recommend future care changes. Stretch features include an AI assistant that interprets system data and offers feedback or

suggestions to the user, helping simplify long-term plant care and enabling more personalized support.

2.5 Diagrams

This section presents visual diagrams that summarize the layout and subsystem relationships within the Bio-Sense Pot. These diagrams were developed to clarify both the physical configuration of the system and the logical flow of information between components. Included are a block diagram illustrating system communication, software flow charts showing system processes, and an optical diagram displaying the optical subsystems. These visuals serve to support both documentation and prototyping by making the design structure easier to interpret and verify.

2.5.1 Hardware Block Diagram

The BioSensePot hardware block diagram outlines the integration of key electronic, optical, and mechanical components for automated plant care. At its core, an ESP32 microcontroller manages sensor data processing, power distribution, and wireless connectivity. A rechargeable 3.7V Li-ion battery, supported by a 5V solar panel, ensures continuous operation. The grow light system, controlled by spectral lighting algorithms, is paired with an internal diffuser to achieve uniform illumination, while an external diffuser refines ambient light measurements for accurate spectral analysis.

Watering automation is achieved through a 5V submersible pump, soil moisture sensor, and ultrasonic water level detection for real-time irrigation control. Environmental monitoring includes a temperature/humidity sensor and a light intensity sensor, feeding data to an AI-driven growth prediction system. The user interface comprises an LCD screen and menu buttons, with wireless connectivity enabling remote monitoring. This architecture ensures precise plant care, optimizing light, water, and environmental conditions with minimal manual intervention.

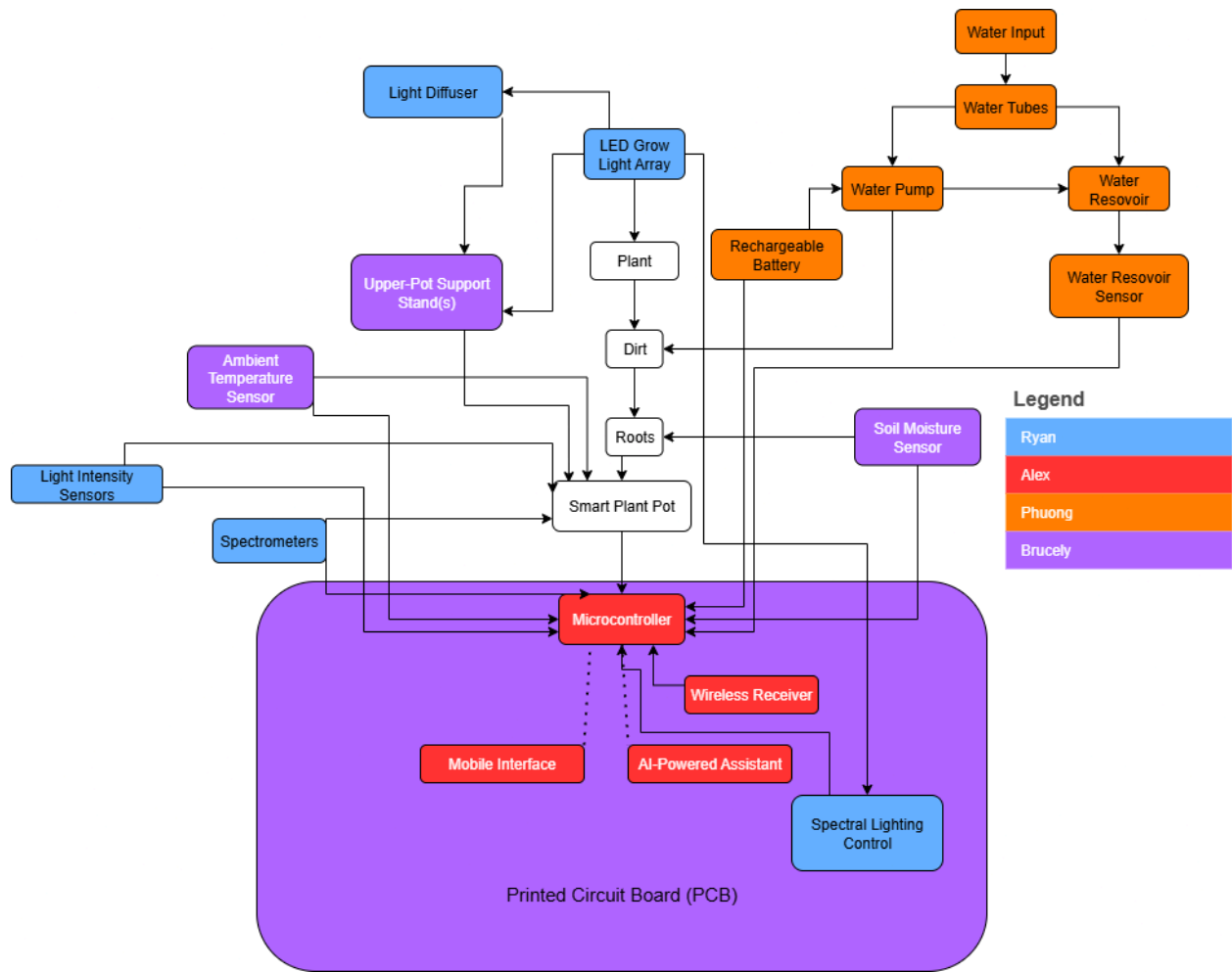


Figure 1: Hardware Block Diagram displaying the connection between key system components and who is responsible for each.

2.5.2 Flow Charts

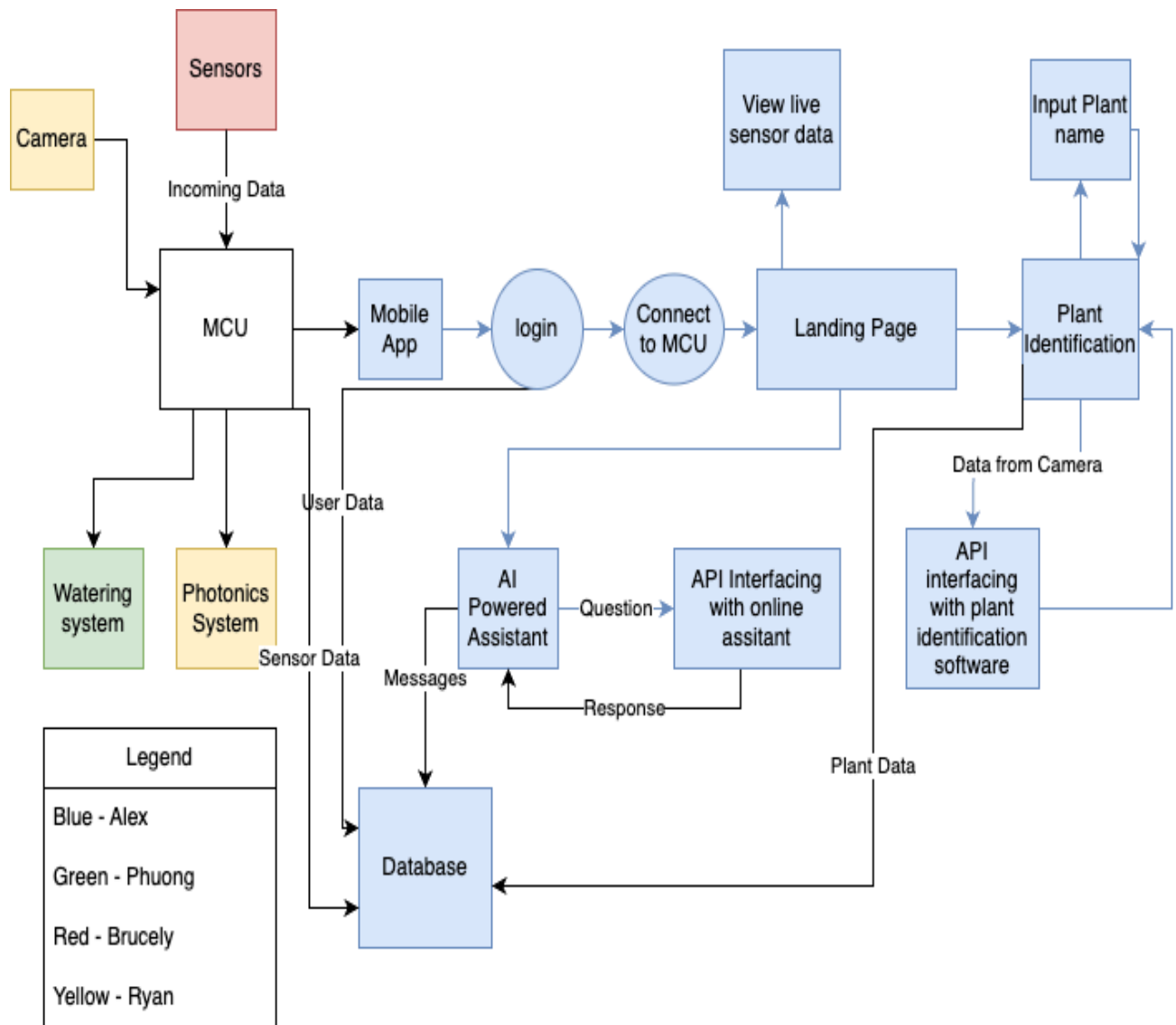


Figure 2: Software flow chart detailing basic systems and software junctions as well as what flow between them and who is responsible for each.

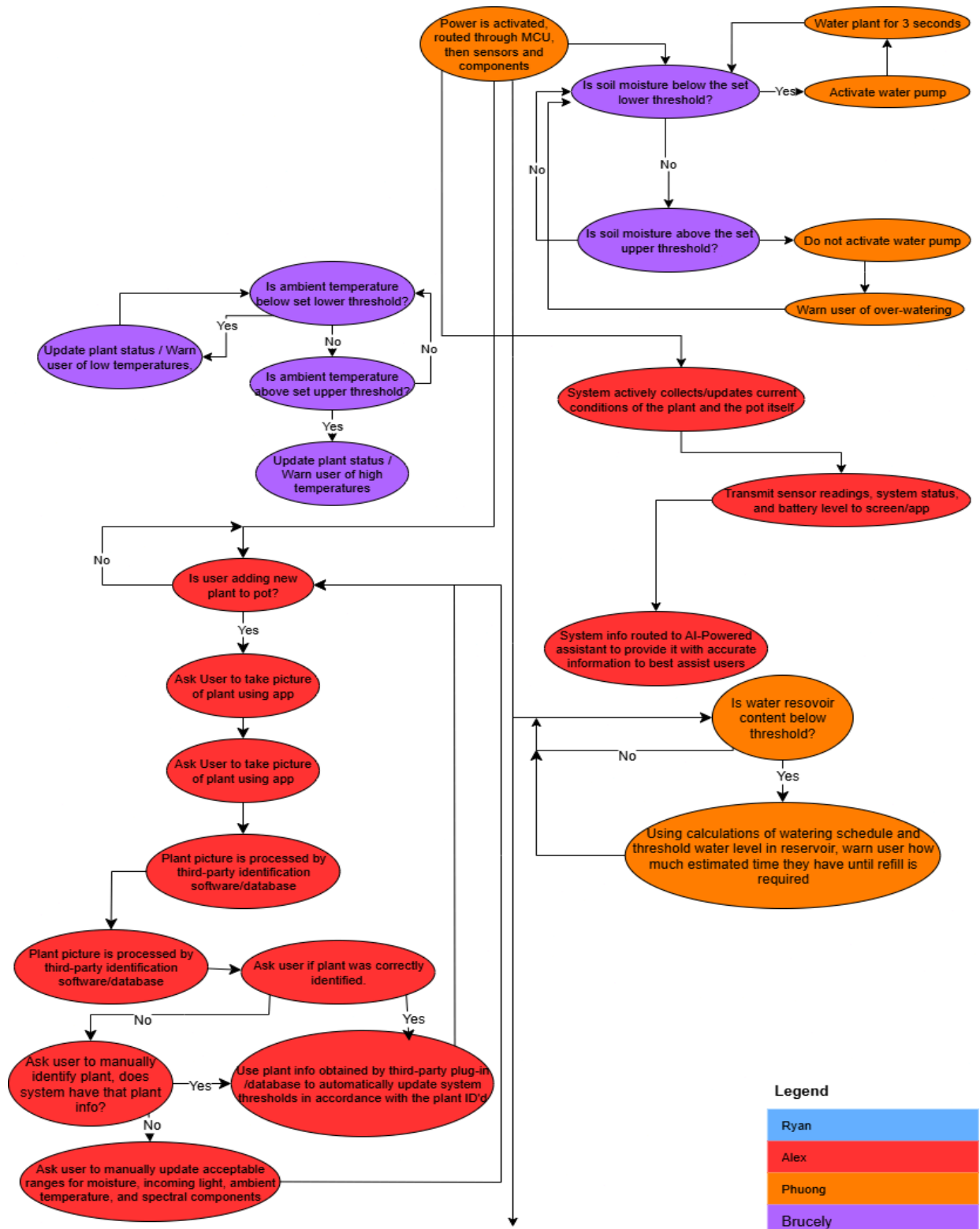


Figure 3: Flow chart detailing the general flow of system processes and who is responsible for them. This part of the chart covers temperature, moisture, system information, and user interaction.



Figure 4: Continuation of the general system processes flowchart, this time focussing on optical systems and power management.

2.5.3 Optical Design Diagram

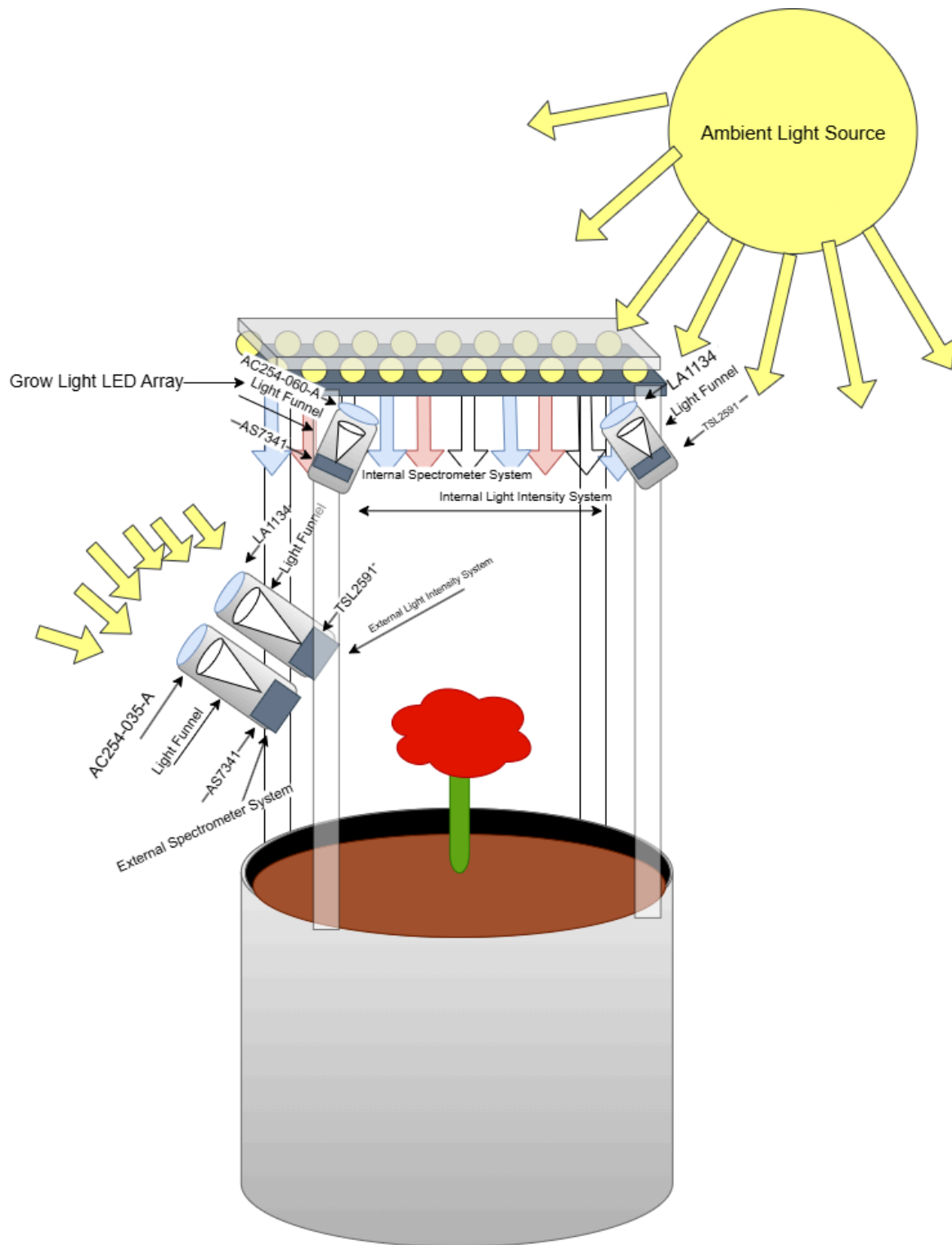


Figure 5: Figure showing the positioning and action of the optical subsystems.

2.6 Requirements and Specifications

This section defines the technical and performance requirements that the Bio-Sense Pot needed to meet to satisfy its design goals. Specifications were broken down by subsystem and include parameters such as voltage ranges, sensor resolution, response times, and enclosure dimensions. These requirements were used as benchmarks during testing and integration, ensuring each component and system behavior aligned with the broader engineering objectives established earlier in the design process.

2.6.1 Requirement Specification:

System	Component	Relevant Specifications
Environmental Monitoring	DS18B20 (Temperature Sensor)	Accuracy: $\pm 0.5^{\circ}\text{C}$ from -10°C to $+85^{\circ}\text{C}$; Supply Voltage: 3.0–5.5V Digital 1-Wire Interface
Spectral Analysis	AS7341 (Internal and External Spectrometer)	Wavelength Channels: 8 visible + NIR; Spectral Range: 415–680 nm Interface: I2C
Adaptive Lighting	TSL2591 (Internal and External Light Sensor)	Dual photodiodes (IR + visible) Lux Range: up to 88,000 lx Interface: I2C
	LED Grow Light System	Red (660 nm), Blue (450 nm) Power: ~5–10W PWM-capable driver Input Voltage: 5V
	Internal Diffuser (TBD)	Foam, PLA, or paper-based Designed for uniform canopy diffusion Under evaluation
Moisture Detection	Capacitive Soil Moisture Sensor	Operating Voltage: 3.3–5V; Analog Output; Corrosion-resistant PCB coating; Typical Range: 0–100% VWC

Water Level Sensing	Optical Water Level Sensor	IR laser + beam splitter + dual photodiodes; Detection Time: <2 min; Mounted externally
Irrigation System	Mini Submersible Water Pump	3–5V; Flow Rate: 100–200 L/h; Digital control via relay or MOSFET
	Solenoid Valve	12V; Inline control of water flow; ON/OFF digital input
Power Management	Lithium-ion Battery (3.7V)	Capacity: ~2500 mAh; Rechargeable; Provides regulated output
	Solar Panel	Output: 5.5V, 1–2W; Used for supplementary charging
	Voltage Regulation Modules	5V Boost Converter (Efficiency ~85%); 3.3V LDO (Low Quiescent Current <100 μ A)
Control System	ESP32-WROOM Microcontroller	Dual-core 240 MHz; I2C, SPI, UART, ADC; Wi-Fi + Bluetooth; Operating Voltage: 3.3V

Figure 6: Table detailing the broad-strokes components requirements for the project's respective systems.

Parameter	Specification and Engineering Requirement	MR#
Dimensions (Pot Housing)	Must fit within 25 cm × 25 cm × 35 cm to ensure all subsystems are enclosed and suitable for desktops or small tables	MR1
Weight (Pot System)	Must remain under 2.5 kg so that the system can be repositioned easily by the average user	MR1

Grow Light Output		Red (660 nm) and Blue (450 nm) channels must be adjustable via PWM to support spectral tuning for different plant stages	MR2, MR4
Internal Sensor	Light	TSL2591 must detect 0–88,000 lux with $\pm 10\%$ accuracy to measure grow light reaching the plant	MR2, MR4
External Sensor	Light	VEML7700 must detect ambient light from 0.01 to 100,000 lux to enable adaptive light reduction	MR2
External Spectrometer		AS7341 must detect RGB and NIR bands (415–680 nm) for analyzing ambient light composition	MR2, MR4
Internal Spectrometer		Custom setup must distinguish at least 3 major spectral bands from grow light to inform spectral balance logic	MR4
Moisture Sensor		Capacitive sensor must detect 0–100% VWC with $\pm 10\%$ tolerance to trigger watering at the correct hydration level	MR3
Temperature Sensor		DS18B20 must detect temperature from -10°C to 85°C with $\pm 0.5^{\circ}\text{C}$ accuracy for system alerts and monitoring	MR2
Water Detection	Level	IR-based sensor must detect empty and full tank states within 2 minutes to avoid irrigation failure	MR3
Water Pump		3–5V pump must deliver ~ 150 L/h and activate automatically when soil moisture is below threshold	MR3
Solenoid Valve		12V solenoid valve must regulate inline flow, opening only during watering to avoid passive leakage	MR3
Power Source (Battery)		Rechargeable 3.7V lithium-ion battery must support ≥ 6 hours of operation without sunlight	MR5
Power Source (Solar Panel)		Solar panel must output $\geq 5.5\text{V}$ at 1W to assist with charging and extend system autonomy	MR5
Voltage Regulation		Boost to 5V and LDO to 3.3V must supply consistent voltages to grow light, microcontroller, and sensors	MR5
Microcontroller		ESP32 must handle wireless comms, PWM, I2C, ADC, and logic for all optical and environmental sensors	MR6

User Interface	System must display real-time data and warnings on LCD screen and allow manual overrides through button/app	MR6
Remote Access	Wireless module must support remote monitoring and control of irrigation and lighting parameters	MR7
AI Assistant	AI-based system must interpret sensor data and provide basic care recommendations via UI or app	MR7
Spectral Adjustment Logic	Grow light spectral balance must adjust automatically using ambient light input from spectrometers	MR2, MR4
LCD Dome (Stretch Goal)	Switchable LCD film must reduce incoming light by $\geq 60\%$ when ambient conditions exceed light tolerance	MR4
Safety & Reliability	All power and water-handling subsystems must be waterproofed and fuse-protected for safe, long-term operation	MR8
Cost Target	Final prototype must stay under \$100 in total part costs (excluding dev tools and test equipment)	MR1

Figure 7: Table detailing system requirements and our expectations for systems and functions.

2.6.2 Marketing Requirements

1. It should be easy to transport and suitable for indoor and outdoor use.
2. Plant health of soil moisture, temperature, ambient light spectra (and spectral composition), and incoming light intensity should be provided continuously and reliably by the system.
3. Extended periods without user intervention should be possible.
4. When there is little natural light, solar lighting should be able to support plant growth.
5. Solar power is one of the most environmentally friendly options, and it should be energy-efficient.
6. Users must be able to easily use the user interface.
7. Monitoring and remote management must be enabled by data logging and potentially artificial intelligence connectivity.
8. Installations must be safe to operate, free of leaks and electrical hazards.
9. The product must be designed in a size and weight range that is manageable by average consumers.
10. System cost should be low enough to allow consumers to buy it but still efficient.

2.7 House of Quality

This section includes the House of Quality (HoQ) matrix developed during early-stage design planning. The matrix maps user needs to engineering characteristics, helping the team visualize how specific technical decisions impact the overall system. It also identifies trade-offs between competing requirements and highlights which features carry the greatest weight in meeting functional expectations. The HoQ was used as a reference throughout the design process to maintain alignment between design efforts and project priorities.

Engineering Marketing Trade Off Matrix

Table 2.7

	Power Consumption	Sensory Accuracy	Automated watering accuracy	Wireless speed and accuracy	Cost
App interface	↓	↑	↑	↑	↓
Automated Control System	↓	↑	↑	↑	↓
Cost	↓	↓	↓	↓	
Wireless Connection	↑		↑	↑	↓

Using the Engineering Trade Off Matrix in Table 3.5, we show the relationships among different system attributes that are positive or negative. To detect plant health and toxicity, the laser based detection system depends heavily on precision spectral analysis of leaf coloration. In the same way, the Automated Plant Care system improves efficiency and ease of maintenance in plant growth optimization by improving multiple features. There are mixed correlations between Automaticity and Connectivity and Capacity Power, suggesting that while power capacity supports automation and connectivity, it compromises portability, cost effectiveness, and size. A strong positive correlation exists between AI driven application interfaces and cost effectiveness, indicating that advanced AI features might increase system complexity and cost.

Table 2.7

	Power Consumption	Sensory Accuracy	Automated watering accuracy	Wireless speed and accuracy	Cost
Power Consumption		↓			↓
Sensory Accuracy	↓		↑	↑	↓
Automated Control System	↓	↑	↑	↑	↓
Wireless speed and accuracy		↑	↑		↓
Cost	↓			↓	

Final setup of the house of quality:

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Correlations	
Positive	↑
Negative	↓
No Correlation	

It is shown in this diagram that there is a trade-off to be made between the two requirements, ensuring that the final product meets the user's needs while still remaining affordable and efficient. There are a number of objectives that are considered in the analysis, such as user-friendly app interfaces, precise automated watering, and cost-effective design. As a result of combining both diagrams' information, we have been able to refine the capability of the smart plant pot by balancing technology with consumer expectations, resulting in a well-integrated and innovative product.

Chapter 3: Research and technologies comparison

This chapter examines related technologies and existing systems to evaluate how they align with or differ from our approach. By studying current methods used in plant monitoring and smart pot systems, we identify practical design features, common limitations, and areas for potential improvement. The goal is to compare the functionality and complexity of available solutions against the requirements of our project, particularly in relation to electrical systems, dynamic lighting, real-time sensing, and adaptive system behavior.

3.1 Existing technologies

In order for us to be able to create a smart pot plant, which can detect plant health and app interfaces, we have to take a look at many different types of smart pot plants and their uses in order to come up with a solution. As we watch many other existing technologies, we examine the limitations of them and see if there is anything we can change or fix to make them more effective. This approach allows us to identify the strengths and weaknesses of existing smart pot plants, understand the specific needs and challenges in detecting toxicity and color, and apply this knowledge to develop a more effective and innovative solution.

Ivy smart Plant Pot

I would like to share with you one of the videos that served as the inspiration for the development of our optical laser system for detection of plants and the smart monitoring pot. Using the setup, you can see a compact, plant monitoring system that provides a live display of environmental conditions, including water level, light intensity, and temperature, enabling you to monitor your plants in real-time. We are developing an adaptable, self-regulating plant system that controls the environment by installing custom lighting, and temperature sensor in order to make the plant system adaptive and self-regulating.

In the video, there was a lot of strength, including a compact, integrated system that displays essential plant conditions in real-time, a user-friendly interface that makes it easy for users to visualize data, and an explanation of key environmental factors that affect plant health (light, water, and temperature). There are some weaknesses in this project such as the fact that the system is small and not suited for large-scale

applications, that it only monitors conditions without actively regulating them, and it lacks advanced sensors for plant detection or app interface analysis.

In our design, we improve upon this concept by allowing for automation and integrating optical laser-based plant analysis for both plant health and app interface identification to better meet the needs of our customers.

Smart flower Pot from Tommy Feng

In this video, we see a demonstration of an automated plant care system which uses sensors to monitor soil moisture levels, temperature levels, and light intensity to automatically adjust watering and environmental conditions based on these measurements. The plant is provided with optimal water and light levels by the sensors based on the data obtained by real-time sensors, ensuring that the plant gets the right amount of water and light to thrive. A number of strengths in this project include the fact that sensors directly control the water pump, lighting, and temperature of the room. A modification could also be made to work with more than one plant or different kinds of sensors so that it works with multiple plants. The main weakness I noticed during the video was that it cannot detect plant health or use app interface accurately, as well as the fact that it does not have advanced AI-driven analysis or remote monitoring capabilities.

It is clear from the development of this system that it aligns well with our project goals, especially in terms of automated watering and environmental regulation. Our vision is to extend the concept of plant analysis using laser-based technology and integrate AI technology to monitor plants.

Light Intensity Project

Here is the video that demonstrates how the light intensity is measured using a sensor in order to illustrate how it focuses on analyzing the light intensity. I was pleased with the speed and accuracy with which the sensor was connected to the other components. As we watched as the sensor measured the light levels in the room, we were able to see how the room was lit up. As soon as they used a light camera and placed it close to the sensor, they were able to measure the intensity of light immediately and with great accuracy the light intensity changed instantly. As a result, we were able to analyze it from a deeper level, allowing us to see its strengths and weaknesses in greater detail. One of the strengths of this product was the fact that it was highly accurate and easy to integrate with ESP32. Due to the fact that this was only a project for light intensity, the simplicity of the project would be too small for a group project. However, we were able to gain some insight as to how we want our sensors to be placed and where they should be placed in our project. It is our intention to utilize a similar light sensor in our project to use solar lights while integrating automated adjustments using LED grow lights and shading mechanisms at the same time.

Transmitting Data With Light

In this video you will be able to see how fiber optics can be used to transmit light by using numbers in order to transmit light. With the help of this project, we are able to gain a basic understanding of how we can be able to receive numbers that have been transmitted using optics. There are several strengths of this project, such as the fact that light can be used to communicate, the fact that low power at high speed and accurate data transmission is provided, as well as its connection to the ESP32 which is a common microcontroller. As a result of the weak fiber optics and the need for precise LED calibration, it may be difficult to implement in an outdoor environment, and some of the sensors may affect the accuracy of the system. When it comes to data communication, sensor accuracy is one of the most important factors since it ensures that the information being sent remains accurate and trustworthy. The use of inaccurate sensors can lead to errors in data collection, misinterpretation, and perhaps even communication problems. It is vital to ensure that fiber optic sensors are calibrated precisely in projects that involve fiber optics so that high-speed and accurate data transmission can be maintained. Despite the fact that fiber-optic communication may not be directly used in our project, this research informs our understanding of laser interactions with plant surfaces, helping us refine our spectral analysis and optical monitoring methods in the future.

3.1.1 Research Result

A key part of this research involved showing the main important videos that influenced the design of our project. During the process of creating our project, we also explained to you the strengths and weaknesses that we saw in each video that we tried to explain to you. As a team, we then concentrated on the practical applications, the design applications, as well as the limitations on the parts that we would require when creating our project and the parts that we would not need. Additionally, these resources inspire innovative solutions and facilitate a more informed approach to integrating advanced optical technologies into our project by aiding us in the development of innovative solutions.

3.1.2 Part Selection

During this section of the project, we will begin to use those innovative ideas and practical applications that we have already discussed in order to discover what parts will be required and what will be compatible with our BioSense Pot project. In order to find out where the parts will be available as well as the quality of the part, we look at a variety of websites. Furthermore, we also had to look into whether or not the part would be in our EasyEDA (software program that allows us to build schematics and PCB boards) because that is where we are going to be building the board with parts. Also,

we had an opportunity to investigate the common optical components that can be found on the market and in CREOL's lab as well. Due to the fact that some components were not available that were a perfect fit for our design, we had to make some small compromises to achieve our design in order to make the component functional.

3.2 Temperature Sensor

3.2.1 Thermocouples

In thermocouples, two dissimilar metal wires are connected at one end, resulting in a voltage proportional to temperature difference as a result of the Seebeck effect, which is a method in which temperature can be measured. There are several key features that make these sensors stand out from the rest, including their wide temperature range (approximately 200°C to 2300°C) and their fast response times, making them suitable for use in high-temperature and dynamic environments. As well as being self-powered and rugged, thermocouples have been found to be suitable for a wide variety of industrial applications due to their versatility. In spite of this, they have nonlinear output capabilities and lower accuracy as compared to other sensors, resulting in the need for complex calibration in many cases. There is also a risk that they are susceptible to electrical noise, which can affect the precision of their measurements.

3.2.2 RDT resistance temperature detector

Temperature resistance sensors are a material that detects temperature fluctuations based on the electrical resistance of the material that is being used to measure them. It is crucial when looking at different types of sensors that you make sure that not only are the accuracy and efficiency of the sensors being considered, but that our numbers are also able to keep up with the other calculations. A number of aspects would be involved in this project, including automated water systems and automated lights, as well as the rest of the project's other components. The resistance temperature detector is highly accurate and stable over a wide range of temperature ranges, but is restricted to certain Celsius ranges, specifically negative 300 ° Celsius to 900 ° Celsius around that range. In terms of price, resistance temperature detectors are very expensive when it comes to cost, and they also have a slow response time due to the environment's rapid changes, such as if the room inside the air is switched on or off, or even if there is a fan in the room where the flower part is situated. Due to the fact that the resistance temperature detector also demands a lot of power to function, it can result in a lot of heat that is not being caused by the surroundings of the environment, but is actually caused by the system itself, which is also detected on the sensor, so we can restrict the amount of space if we have a ventilation system or power system for that component, while we have other components that will be on our project as well. In order to get an accurate resistance temperature detector, there are two types of combinations that need to be taken into account. These combinations are resistant tolerance and temperature coefficient of resistance tolerance. Hence, it is clear from the graph that, when the tolerance band is outside the range of temperature, it will have a lower degree of accuracy. Further, by learning more about the range of accuracy that they can provide

us with, it has helped me to understand that when choosing the sensor that we need for our application that we will be able to consider what are the ranges of accuracy that they can provide us with.

3.2.3 Semiconductor Temperature Sensor

In terms of temperature sensors, semiconductor-based sensors are widely recognized for their high accuracy as well as their temperature range which typically ranges between -60°C and 180°C . It is important to note that these types of sensors are based on the fundamental temperature characteristics of semiconductor materials, which are characterized by a predictable change in output voltage or current as a function of temperature. As a result of the transistor's current response to temperature, semiconductor sensors are most commonly used for applications that require precise and consistent readings, as they are designed to measure the current response to temperature. However, semiconductor temperature sensors do not come without their own set of challenges despite their high efficiency. The main concern is self-heating, which occurs when the sensor is activated for extended periods of time and consequently affects the readings of its own temperature due to the effect of self-heating. Without proper thermal isolation or periodic cycling of power, this can lead to inaccuracies in the measurement process if not properly managed. Furthermore, external heat sources and circuit noise can interfere with the accuracy of the readings, making it necessary to maintain accuracy by calibrating and shielding the instrument. The advantage of these sensors is that they offer a number of advantages that make them an attractive choice for many applications that are common today. Because of their small size, compact size, and lightweight, they can easily be integrated into digital systems as well as microcontrollers, making them a perfect choice. There are several advantages to linear outputs such as the fact that they simplify the signal processing and reduce the need for complex conversions, as well as the fact that they are cost-effective, which provides a good balance between affordability and performance. It is important to note that semiconductor temperature sensors, when calibrated correctly, can deliver accurate and stable measurements, making them a popular choice for smart agriculture applications, climate control systems, and medical devices.

Comparison:

There are three different types of sensors we can compare in this section, these are the Semiconductor temperature sensor, Temperature Detector, and the Thermocouple. In order to choose the best in accuracy, durability, response time, and cost effective, you need to consider a variety of factors. For instance, if we take a look at the first option which is terminal couples, we will find that they are the most durable and they can withstand extreme temperatures, therefore making them the best choice for a wide variety of industrial applications. It is important to note that, despite these tendencies, the accuracy of the heat signature on the heat output 10 may fluctuate over time due to these trends. There are also resistant temperature detectors that provide accuracy and stability, but they are fragile and require a great deal of power, and due to the fact that they require a lot of power, there may be additional components that we have to put into them, such as ventilation or even a fan. Last but not least, when it comes to

semiconductors, it is evident that they offer many good qualities such as being compact, low cost, and have digital outputs making them ideal components that could be used in our project. In addition to this, these three types of sensors are also restricted in terms of the temperature range between -200 degrees Celsius and 850 degrees Celsius. Here we will see what the differences between these components are, as well as the reasons why we decided to use the semiconductor temperature sensor as opposed to the others.

Feature	Thermocouples	RTDs	Semiconductor Sensors
Variation of temperature	-200°C to 2300°C	-200°C to 850°C	-60°C to 180°C
Precision of Accuracy	Moderate ($\pm 1^{\circ}\text{C}$ to $\pm 2^{\circ}\text{C}$)	High ($\pm 0.1^{\circ}\text{C}$ to $\pm 0.5^{\circ}\text{C}$)	High but it has to be calibrated correctly. ($\pm 0.5^{\circ}\text{C}$ to $\pm 2^{\circ}\text{C}$)
Response Speed	Fast (1 second to 2 seconds)	In between slow and moderate (2 second to 8 seconds)	Fast (1 second to 3 seconds)
Cost	Moderate (\$3 to \$15 per sensor)	High (\$10 to \$50 per sensor)	Low (\$1 to \$5 per sensor)
Durability	High (Lasts 5 to 10 years, rugged)	A moderate level of fragility (more fragile than thermocouples)	Low to moderate (More prone to damage, 1–3 year lifespan)
Output Type	It outputs a non-linear voltage	Linear resistance change	Digital or analog output
Best For	Industrial applications, high-temperature environments	precision monitoring	Smart plant monitoring small projects

3.2.1 Part Selection

LM35

In addition, the LM35 temperature sensors are widely used in a wide variety of applications, each with their own advantages and limitations depending on the environment in which they are used. This is an analog temperature sensor that is capable of providing a linear voltage output directly proportional to the temperature in Celsius. A linear voltage output is directly proportional to the temperature within a wide range of -55°C to 150°C to ensure high accuracy of 0.5°C within this operating range. There is no doubt that it has one of its strongest points in that it consumes little power, making it suitable for systems that are powered by batteries. In addition to that, it is not required to be calibrated, making integration a lot easier. Nevertheless, it has an inherent limitation in that it requires an Analog-to-Digital Converter (ADC) for microcontrollers that lack built-in ADC capabilities, and its accuracy can fluctuate due to variations in the supply voltage and self-heating, so careful circuit design is essential.

DHT11

The DHT11 is a semiconductor-based digital sensor that accurately measures both humidity and temperature, making it a reliable choice for environmental monitoring applications. Its ability to operate within a temperature range of 0 to 50 degrees Celsius and a humidity range of 20% to 90% makes it highly adaptable for smart plant monitoring systems and indoor environmental control. The DHT11 is known for its cost-effectiveness, making it an ideal option for budget-friendly applications that require basic climate data collection. With its low power consumption, it can be efficiently integrated into battery-operated devices, ensuring long-term operation without excessive power drain.

One of the key advantages of the DHT11 is its simple communication protocol, as it uses a single-wire data interface and a three-pin connection for easy microcontroller integration. This minimizes wiring complexity and allows it to be used with popular development boards like Arduino, ESP32, and Raspberry Pi. However, despite its practicality, the DHT11 does come with certain limitations. It has a slow sampling rate of one reading per second, which makes it less effective for real-time applications that require frequent updates. Additionally, its narrow temperature range limits its use in extreme climate conditions, making it unsuitable for high-precision industrial or scientific temperature monitoring.

DHT22

It is worth noting that the DHT22 is a revision of the DHT11, which is to say that it is a lower cost version of the DHT11 and also that the capabilities of the measurements have been improved dramatically, which are 40°C to 80°C for the temperature measurements and 0% to 100% for the humidity measurements. In this way, the DHT22 becomes a more accurate system and is able to measure the surrounding area and space out digital measurements according to PIN numbers. Having it on hand when doing the small flow power plant project and being able to take measurements every two seconds will make it a more suitable application for what we are trying to accomplish. Although there are some limitations when comparing the cost-effectiveness of DHT22 with DHT11, there are always some things to keep in mind when comparing

the two. In general, the DHT22 provides a better function than three components, which is why we decided to use the DHT22 in our semiconductor temperature sensor instead of using the three components.

Comparison

In our review of the three components, which are the DHT11, DHT22, and the LM 335 sensors as part of our small plant monitoring system, we decided that the DHT22 would be the best choice for the monitoring system. While the DHT11 can be seen as a very cost-efficient sensor, it is not more accurate or reliable than the DHT22 in terms of accuracy or reliability. Unlike the LM35, which offers high accuracy for the measurement of temperature, the LM35 does not offer high accuracy for the measurement of humidity. Using the component of the DHT22 as part of our senior design project, it provides us with a balanced accuracy for both temperature and humidity measurement, which is crucial for the success of the project. As a result of the DHT22's rugged design, it is suitable for use in a variety of environmental conditions. We are going to review the three components in the table below and we will be comparing the advantages and disadvantages of each of them. In some sections there will be advantages and in others there will be disadvantages.

Feature	DHT11	DHT22 (Selected)	LM35
Temperature Range	0°C to 50°C	-40°C to 80°C	-55°C to 150°C
Humidity Measurement	Yes up to 20% to 90%	Yes up to 0% to 100%	No
Accuracy (Temperature)	Plus or minus 2	Plus or minus .5	Plus or minus .5
Accuracy (Humidity)	Plus or minus 5%	Plus or minus 2%	Plus or minus 5%
Response Time	Slow in about 1 read per second	Moderate (about 0.5 to 1 seconds)	Fast (less than 1 second)
Output Type	Digital	Digital	Analog
Cost	Low (\$1 to\$ 4)	Moderate (\$3 to \$7)	Moderate (\$5 to \$10)
Ease of Integration	Simple single-wire interface	Simple single-wire interface	Requires ADC for digital integration
Best For	Basic smart plant monitoring, budget-friendly applications	High-accuracy smart plant monitoring, environmental	Precision temperature measurement, industrial

		control	applications
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3.3 The Technologies for soil moisture

We are going to provide you with a general overview of soil moisture and explain what a soil has to have in order for it to be moist. In order to manage and grow plants in a productive manner, soil moisture measurement is a crucial part of plant life management and development. This will allow us to be able to make a calibration or even measurements on if the plant needs a certain amount of water because there are many different plans that require a certain percentage of water, and we do not want the plant to drown or become dehydrated since it is not getting the water that it needs. Using these technologies will allow us to understand so much more about how to monitor so many levels and what are the best capabilities of these products, as well as what are their faults and liabilities in these products.

3.3.1 Capacitance sensors

The capacitive sensors are used to measure the amount of moisture in soils by measuring the dielectric permittivity, which varies depending on the amount of water contained within the soil. There are many advantages to using capacitive sensors, such as the quick response time and the accuracy of the readings when properly calibrated. As a result, we will also be able to work out in real time how to interpret the measurements and the actor silver data that has been collected as part of our project. In spite of this, the accuracy of the model can sometimes be affected by the properties of the materials, such as salinity, clay content, temperature, and bulk density. In all of these pictures, there is a major role for the fluctuation of the measurement to play in the measurements. In addition to this, they have a small sensor area, which will not be able to provide accurate measurements for the moisture level of a large area of the field due to its small sensing area. There is a need for regular maintenance on the capacitor sensors in order to maintain their precision and accuracy.

3.3.2 Time Domain Reflectometry

This time domain reflectometry method gives some information about how long it takes for an electromagnetic pulse to travel along a device which will be inserted into the soil during the time domain reflectometry method. In addition to the high accuracy and great response time that TDR sensors can provide, they can also be used in a wide range of soil types. It is very useful when you have a farm or similar type of large area where a lot of crops will be grown at the same time for a rapid response time, and this sensor can be very helpful. Despite the fact that these sensors are very cost effective, it is very unlikely that this will be implemented in the project due to the fact that they are very expensive. Furthermore, a complex operation such as this requires expertise or someone who has the knowledge and experience to create it, which may limit their use in certain applications that require it.

3.3.3 Resistive (conductive) sensors

In order to measure the electrical resistance between electrodes placed in the soil, the resistive sensors use two electrodes as sensors. This can cause a problem because as moisture content in the soil increases, the amount of electrons in the soil will decrease as time passes. There is a large range of applications for this type of sensor because it can work with any type of hardware component, is very resistant to corrosion and fouling, and can provide quick and accurate measurements of the soil moisture when the soil moisture fluctuates. Nevertheless, there are some downsides to using these types of resistor sensors, such as high power requirements, which can result in heat output towards the plant and if there are multiple other components in the system, it might dehydrate or even kill the plant more rapidly. Furthermore, these types of parts require a lot more calibration and maintenance since they are not as stable for use over a long period of time.

3.3.4 Tensiometers

There are tensiometers in the plan that are able to measure the tension and suction when the plant pulls water from the soil, which is able to provide information about the soil water levels. Tensiometers are often used to provide quantitative measurements of the soil with the aim of understanding the water content within the soil moisture which is very important when it comes to determining the water availability within the soil. As this sensor is very cheap, it is very accurate and it is not affected by the salinity of the water or its temperature. It is also very easy to use. On the other hand, there are some disadvantages when it comes to this technology, including a slow response time, a small sensor area, and a limited range.

Feature	Capacitance Sensors	Time Domain Reflectometry (TDR) Sensors	Resistive (Conductive) Sensors	Tensiometers
Measurement Method	Measures dielectric permittivity	Measures electromagnetic pulse travel time	Measures electrical resistance	Measures soil water tension
Accuracy	Moderate to High (requires calibration)	High ($\pm 1\%$ to $\pm 3\%$)	Low to Moderate ($\pm 5\%$ to $\pm 10\%$)	Moderate ($\pm 3\%$ to $\pm 5\%$)
Cost	Moderate low (\$10 to \$30)	Expensive (\$50 to \$200)	Low (\$3 to \$10)	Expensive (\$100 to \$200)
Sensitivity to	Affected by	Works well	Influenced by	The plant is

Soil Type	salinity, clay content, and bulk density	across various soil types	soil salinity and temperature	best suited for some types of soils (not for very dry soils)
Durability	Moderate (enclosed in plastic indoor/outdoor use)	High (Designed to withstand rugged outdoor use)	Low (Susceptible to corrosion and probe damage)	Moderate (delicate glass or ceramic parts; best in stable setups)
Maintenance Requirement	Calibration is required frequently	Not much	There is a need for frequent calibration and replacement	Occasionally needs to be maintained (refilling and cleaning)
Best For	An easy way to measure soil moisture, precision agriculture	A high-precision irrigation monitoring system	Monitoring agriculture at a low cost	Control of irrigation and water availability in plants

3.3.5 Part Selection

DFRobot SEN0193

Using the DFRobot sensor, one can measure the resistance and corrosion moisture of soil without having to come in direct contact with the soil. The advantage of using this type of sensor is that as opposed to resistive sensors, it does not suffer from electric corrosion, which makes its lifespan even longer, which makes it a perfect tool for monitoring soil moisture levels. Due to the analog output, this controller can work with many Microsoft controllers, such as the MSP320, Arduino, and Raspberry Pi, which makes this a great fit for integration into an irrigation system that is smart. Despite the many advantages of this product, there are some limitations, such as the analog signal can fluctuate depending on the interference, which requires a good seal for high precision applications. Also, it might need to be calibrated frequently since it is an analog product, and since it is an analog product, there are many other parts that can be taken into consideration when affecting this product. Even though there are some challenges, it has still proven to be a reliable and affordable solution for our DFRobot component in our project, particularly for indoor use.

Vegetronix VH400 Soil moisture

For Vegetronix, the VH400 is a high precision capacitive soil moisture sensor that is designed for scientific and industrial use. As a battery powered sensor, the Vegetronix

provides accurate and precise readings with low consumption of power, which would make it a great choice for applications that require low power consumption and monitoring. Furthermore, this part also offers waterproof and gray durability, which is a feature that allows the part to enable the function to work even under harsh conditions and under wet conditions. Also, it gives the device the ability to not suffer from corrosion or degradation of signal due to corrosion or exposure to water. Due to its high accuracy and durability, however, the Vegetronix soil moisture sensor is, in comparison with all the other soil moisture sensors, a lot more expensive. Nevertheless, it has a number of drawbacks, including a limited availability of stocks and a longer lead time, which can also be a detriment. Furthermore, if you want to achieve maximum accuracy, you need to calibrate the device correctly for a variety of soil types before you use it. As a result, its long life span, high accuracy and reliable performance make it a referred choice for a component that can be used in a wide variety of applications.

Adafruit STEMMA Soil sensor

Adafruit stamina soil sensor is a digital composite soil motion sensor that can be connected simultaneously to a single microcontroller with i2c communication. This allows the soil motion sensor to be connected to four microcontrollers simultaneously without causing analog interference to the single controller. Additionally, by doing so, the noise level and the error level could also be reduced substantially. Furthermore, it incorporates a temperature sensor so that more comprehensive environmental data is available for monitoring the plant environment. In the case of plants monitoring, Disensor is a very good tool for starting out a project, due to the fact that Adafruit offers strong guidance and library support for the project. In spite of this, one of its major disadvantages is the fact that it is much more expensive than the traditional analog sensors, which makes it unsuitable for low-power projects such as those we undertake. It might also be too complex for beginners who are unfamiliar with digital protocols to use the Adafruit interface. While this soil sensor has a few minor drawbacks, it is one of the best options for doing a small project and gaining a better understanding of its components.

Comparison

Each of these soil moisture sensor parts that we have seen has its own set of advantages and disadvantages. While the Dfrobot is affordable and reliable, it requires frequent calibrations, whereas the Vegetronix is very precise and durable, but it costs a lot and requires precise calibration. The Adafruit sensor provides digital i2c outputs, but it may be complicated to use due to its multiple applications and a high cost. It is important to note that when we looked at the best sensor part for our project, we took into account budget, accuracy, and durability, and we found that DFRobot was the best option. Below you will see a comparison between the three.

Feature	DFRobot SEN0193	Vegetronix VH400	Adafruit STEMMA
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	(Selected)		
Measurement Method	Capacitive	Capacitive	Capacitive
Output Type	Analog	Analog	Digital
Accuracy	Moderate ($\pm 5\%$ to $\pm 10\%$)	High ($\pm 1\%$ to $\pm 3\%$)	High ($\pm 1\%$ to $\pm 2\%$)
Durability	Very good (not prone to corrosion)	Very good (rugged, waterproof)	It's good (but not as rugged as the VH400)
Power Consumption	Low (a few mA)	Very Low (1mA to 3mA)	Low (1mA to 5mA)
Ease of Integration	The easiest (Arduino, Raspberry Pi)	Moderate (Needs calibration, specific analog reading scaling)	Moderate (I2C interface, works with Arduino)
Cost	Affordable (\$8 to \$15)	Expensive (\$40 to \$65)	Expensive (\$25 to \$50)
Additional Features	Identification of water vapor	Moisture readings that are highly accurate	Multi-sensor support and integrated temperature sensor
Best For	Plants indoors, smart irrigation, and budget projects	Commercial agriculture	Educational projects,

3.4 Types of Solar technologies

It is important to understand that solar power comprises different types of technologies, each of which possesses a number of advantages and disadvantages. There is no denying the importance of obtaining energy from solar sources for human life due to the ability of solar cells to store light and convert it into energy that can be used for a wide range of functions that require power. There are a few types of solar lights that we would like to choose from which are monocrystalline, polycrystalline, thin film, and concentrated solar power, and our goal is to pick those that are the most efficient and durable.

3.4.1 Monocrystalline

The monocrystalline solar panels are crafted from a crystal silicon, they are efficient and they usually go in a range of 17 to 22%. The structure allows for electrons to flow better, resulting in a greater performance, especially when there is not much space. These solar panels are made out of semiconductor material that helps to convert sunlight into electricity by turning photons into electrons. Most monocrystalline solar panels are black because that's when the light hits the silicone Crystal. This also has the highest power capacity out of all of the other solar panels. These panels also are very heat resistant allowing it to be able to function better and convert light into energy for our project. However, there are some disadvantages when it comes to monocrystalline which are high cost.

3.4.2 Polycrystalline solar panels

The polycrystalline panels are made from silicone fragments, which are then melted together, and have a simple production process, which means that the panels are very cost efficient and can be produced in large quantities. A polycrystalline solar panel has a blue color resulting from the light reflecting off the silicone fragments that make up the panel when the light hits them. In comparison with many other types of solar panels, polycrystalline solar panels have a high resistance to heat. There are some disadvantages to these panels though, such as their poor efficiency around 15 to 17%, and the fact that they require a lot of space to be able to generate the same amount of power as monocrystalline solar panels.

3.4.3 Thin Film solar panels

The thin film panels are able to integrate photovoltaic materials into some surfaces like glass or metal. In addition, a thin film solar panel is lightweight, flexible, and can be integrated with many different applications, including building materials, which can enable it to be one of the most sustainable energy sources available. As opposed to the other traditional solar panels, these solar panels are very thin, and they are made up of solar cells, which are used as the energy source. We believe that this type of solar panel technology would be very useful for our project, since it is lightweight and flexible, so we will be able to construct it and format it the way we wish. They have a short lifespan and a high decoration rate, which can pose problems for the project due to their short lifespan and high decoration rate.

3.4.4 Concentrated Solar power

In concentrated solar power, the sunlight is focused onto a small part of the solar array in order to generate heat, which is then converted into electricity through the use of mirrors. Using solar power is advantageous as it incorporates thermal storage that allows the ability to generate power even when the sun is not shining, which will be very

useful if we incorporate that into our project. Despite this, concentrated solar power is typically suitable for large areas such as farms and large-scale installations where there is a high direction of light and the conditions are more diffuse, making it less effective than its diffuse type counterpart. There are a lot of downsides to concentrated solar power. It is very expensive, and it also requires other subcomponents so that the solar power doesn't become overheated, and it also takes up a lot of room.

Comparison

It is important to note that each of these solar technologies offers its own benefits as well as limitations, making them suitable for different types of applications as well as different environments. In this table, we will be discussing some of the advantages and disadvantages that can be found when it comes to these different types of solar power, such as the efficiency, cost, space, and location, all of which are essential when it comes to choosing the correct solar energy.

Feature	Monocrystalline	Polycrystalline	Thin-Film	Concentrated
Efficiency	high (17-22%)	Medium (15-17%)	Low medium (10-12%)	Very high (up to 40%)
Cost	A high price	Compared to monocrystalline, it is more affordable	Cheaper than crystalline panels	The price is very high
Durability	Very high (long lifespan)	A moderate level	Low durability (short lifespan)	High (long lifespan)
Space Requirement	Low (takes up less space)	Moderate (requires more space than monocrystalline)	Higher (needs a larger surface area)	A very high level (large installations required)
Performance in High Temperatures	Performance is moderate (slight decreases)	Moderate (similar to monocrystalline)	Good (better than crystalline panels)	Inefficient (inefficient in low-sunlight areas)

Flexibility	A rigid structure	A rigid structure	Flexible	A rigid structure
Best Use Case	Rooftops of residential buildings, installations in restricted spaces	Solar setups that are affordable and large solar farms	Buildings with solar integration, portable applications	Located in sunny regions, utility scale solar power plants

3.4.5 Part Selection

Micro Solar Panels with Wire, 5PCS 5V 200mA

Micro solar panels are very compact and are designed for low power applications, which makes them a great idea for small projects since they are designed for low power applications. This solar panel provides a 5 volt at 200 milliamps of power which is enough to power a PCB circuit design and a small rechargeable battery pack. With its lightweight and compact design, the solar panel is easy to integrate into a variety of projects which can be very space-constrained. A major advantage of using this type of solar panel apart from the fact that it is affordable and easy to use, it also comes with pre-wiring so all you have to do is add the additional soldering and you are done. Additionally, they also observe a way to reduce the dependency on batteries by using renewable energy, but this is only applicable to small applications. However, there is one drawback to these panels, which is the low power output, which can be problematic since many of the components that we use require more power than the solar panels can provide. In addition to that, it likes to be weather resistant so it wouldn't be a good plant to put outside because of this. Additionally, this type of solar panel has a lower efficiency as compared to other types of solar panels, which means that it will require more power to produce the same amount of energy that the other type of solar panel would be able to produce.

EF ECOFLOW 100W Flexible Solar Panel with High Efficiency Solar Modules, IP68 Waterproofing

A flexible solar panel has extremely high efficiency and is designed as a portable and energy-saving solution. The best thing about this product is that it can be mounted on a variety of different kinds of terrain such as RVs, boats, campers, and even circular containers where rigid panels would not be compatible because of its flexibility. Aside from that, it is waterproof, which means that it can be used both inside and outside and will be able to withstand the effects of water and extreme weather conditions, making it highly durable for use both indoors and outdoors. In addition, this panel is capable of producing a power output of 100 Watts that is significantly higher than the power output

of many other smaller panels, which allows it to generate more electricity that can be used by many other components of the system. Even though this has many advantages, it also has many disadvantages; for instance, the flexible panel makes it very lightweight and easy to install, but it is less efficient compared to monocrystalline panels due to the fact that it absorbs less sunlight than a monocrystalline panel. Due to the construction of the flexible panels, they have a shorter lifespan than the original panel as a result of the fact they are less suitable for the installation process than the original panel. It is also important to note that these panels are notably more expensive than other panels, so they will not be as cost-effective as other panels will be.

Delinx 4Pcs 5V 6V 1W Mini Solar Panels for Solar Power

With its compact size and lightweight design, the Delinx panel is ideally suited for use in a wide range of projects that require solar energy and is easy to integrate with a wide array of different types of projects. In terms of power output, this solar panel gives out a power output of one Watt, which is actually quite good for smart applications, small LED lights, and battery charging circuits. There is a great deal of flexibility in wiring them together in order to increase voltage, depending on the application. Since it is such a compact size, it makes it ideal to use it in our project, and it will take up much less space than multiple components that would probably take up more space if we used them. Despite these advantages, there are a number of significant limitations, including the inability to produce very large quantities of power, making it unsuitable for large quantities of energy needs. Furthermore, the efficiency of these solar panels is lower as compared to other solar panels, which means that they will require a much longer period of time for them to be exposed to the sun in order to generate a sufficient amount of power. The best use for these devices is for power and large devices, as well as being very affordable and grateful for learning purposes.

Trail Camera Solar Panel, Mini Solar Battery Charger DC 12V/1A 6V/1.5A Build-in

Despite the fact that the trail camera solar panel is a very compact and efficient power solution, and it is designed for use outdoors, we were considering taking advantage of its capabilities for indoor uses. In order to be able to utilize the solar panel on the side of the pot plant structure, we can adjust the direction in which it faces the sun when the sun passes through the window to face the sun whenever the sun passes through. As one of the biggest advantages of our system, we are able to provide a constant and renewable energy source, which means we are able to reduce the need for having to replace batteries whenever they run out. It is very cost-effective to implement this part in our design, and therefore, it is a great solution in terms of cost-effectiveness. In addition to this, it has a battery source built-in, which is a great feature to be able to use with this part of the machine. In spite of this, there are some limitations when it comes to the power output when compared to a larger solar panel. In addition to that, you will have to adjust the positioner and the angle of the unit to ensure that as much sunlight as possible is absorbed, which can be a challenge depending on the weather conditions.

Comparison

In order to determine which solar panel is most suitable for our smart plant pots, we compared four different solar panel options in this table to determine which would be the most effective. Our criteria for comparing the solar panels we selected include their output power, efficiency, size, portability, installation complexity, durability, use cases, costs, limitations, and the best features, since these are the factors that directly affect how well they perform on the solar panel. Due to the fact that our system is dependent on sensors, LED grow lights, and automated components, power output is extremely important. When it comes to efficiency, the effectiveness of the panel determines how efficiently it converts solar energy into usable energy, which determines how long the plant pot can operate without external power. In order for the panel to fit within the plant pot design without being bulky or inconvenient, it must have a good size and portability. During the installation process, we take into account the complexity of the installation since an easy-to-integrate panel will help us save time and effort. In addition to the durability of the panel, it also needs to be resistant to changes in indoor conditions such as humidity and fluctuations in temperature. It is helpful to see which panels work best for small indoor projects compared to large-scale applications by examining the use cases. We also want to find a panel that is affordable, yet effective for our purposes, so we think that cost is a key factor in choosing the right panel. Besides looking at the limitations and the best features, we also take a look at how trade-offs will be made based on the alternative we choose. As a result of comparing these factors, we will be able to narrow down the best solar panel choice, ensuring it meets both functional as well as practical requirements for our clever plant pot system as well.

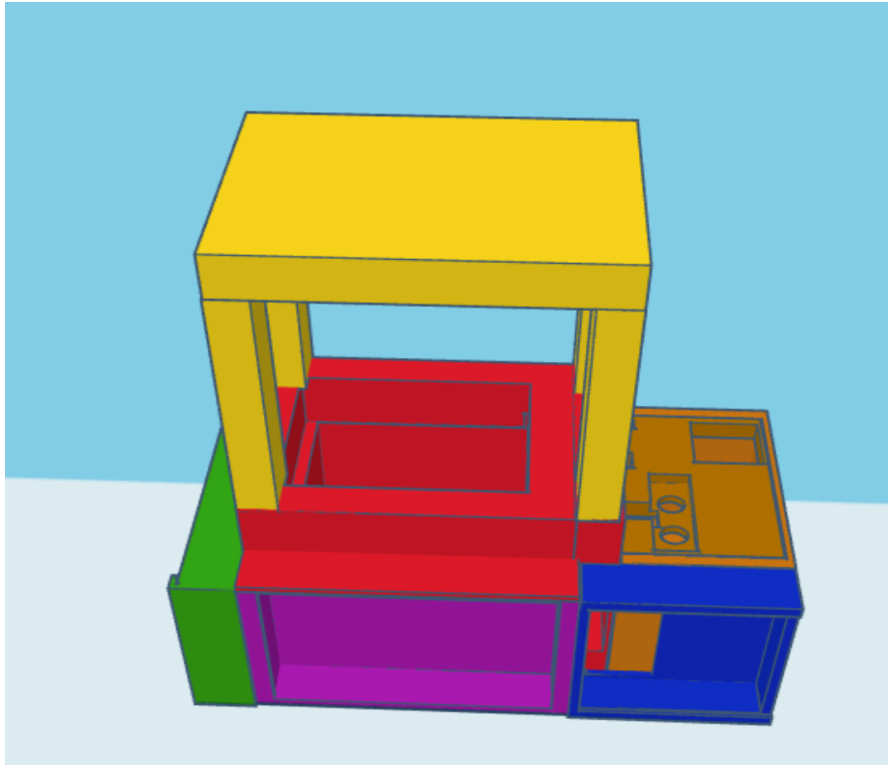
Feature	Micro Solar Panels (5V 200mA) Selected	EF ECOFLOW 100W Flexible Solar Panel	Delinx 5V 6V 1W Mini Solar Panels	Trail Camera Solar Panel (12V/1A, 6V/1.5A)
Amount of power produced	Low (1W Max)	High (up to 100 W)	Low (1W per panel)	Medium (6W to 15W)
Efficiency	Low (10% to 15%)	Medium High (14% to 25%)	Low (8% to 15%)	Moderate (15% to 18%)
Size & Portability	Compact and lightweight	A large and flexible space	It is compact and can be connected in series	Designed for outdoor use, medium-sized
Installation	Wiring is	Mounting and	Arrangements	In order to

	simple and plug-and-play	securing are required	can be made based on your needs	maximize efficiency, it is necessary to adjust the angle
Durability	Suitable for indoor use only	Waterproof and weatherproof	Suitable for small projects, not weatherproof	Weather-resistant, designed for outdoor use
Use Cases	Electronics for small spaces,	off-grid systems	Pots for plants that are smart, small devices	Battery-powered outdoor trail cameras
Cost	Low cost (\$3 to \$6 per panel)	High cost (\$100 to \$300)	Very affordable (\$1 to \$5 per panel)	Low cost (\$20 to \$40)
Limitations	Suitable for smaller loads, but not for larger ones	Inexpensive and space consuming	Efficiencies are low, sun exposure must be prolonged	The power is limited, and sunlight must be positioned for it to work
Best Feature	Easily integrated	It has a high power output and is waterproof	This is a great tool for small projects and it is inexpensive	Battery powered, so you can use it continuously

3.4.6 Upper-Pot Support Stand

As we were thinking of how to make our BioSense Pot to accommodate all the components that we will be installing in our project, we were looking at many different types of structures or products that we can be able to utilize to build our upper pot support stand to support all the components which we will be installing in our project. It was suggested to us that we look at wooden structures and even plastic containers in order to be able to store water that we will need to supply for the automated water system and also to provide a strong support when attaching equipment to them. Initially we try to create our design using drawings as a starting point in order to come up with great ideas as to how we would like our structure to be laid out and how our design should look. Then we used a software application to create a 3D model of how our plan part would be arranged in our project and where all of the components will be attached to the smart pot in order to make it a smart one.

- Yellow (LED light roof and the support beam for light sensors housing)
- Green (Power Supply)
- Red (Container for plants)
- Purple (Main PCB board)
- Blue (Soil sensors pcb board)
- Brown (Water Tank and Ultrasonic sensors housing)



3.5 Auto watering system

The automatic watering system is essential for our project, as it is a key feature found in most smart plant systems. This feature ensures plant hydration without consuming users' time for care. Our watering system will include sensors and AI-driven analytics to maintain moisture levels and optimize water usage. The goal is to use soil moisture sensors to measure the underground moisture level for the plant and send the data to the microcontroller for decision-making. Then, AI algorithms will predict plant hydration

needs based on moisture settings, temperature, and humidity required by the plants to activate watering. We also add an online monitoring system for remote adjustments [50][51][52].

3.5.1 Water pump type

In the industry, there are two general types of water pumps: submersible water pumps and external water pumps. Submersible pumps are designed to operate underwater. Their notable features include low noise, compact size, and suitability for small enclosed systems. External pumps are designed to be placed outside the water source and pull water through tubing, offering easier maintenance and higher durability but requiring more space and producing more noise compared to submersible pumps. To ensure an efficient and reliable automatic watering system, we will point out the pros and cons of each type and choose the one that fits our indoor plant pot project [53][54].

3.5.1.1 Submersible Water Pump

The submersible pump is designed to operate underwater, making it compact, quiet, and efficient for small enclosed systems. It is a great option for our project since it can be directly placed inside the built-in water reservoir, reducing the need for additional tubing and saving space. In our project, we are mainly focused on power consumption, so we plan to choose the 5V mini submersible pump because its power consumption is relatively low, making it ideal for our energy-efficient design with solar backup compatibility. However, this type of pump requires a filter to prevent clogging, and maintenance is more difficult since it must be removed from the reservoir for cleaning or replacement. While it is a great fit for our project due to its small size and silent operation, careful design considerations are needed to avoid potential clogging and ensure long-term durability [55][56][57].

3.5.1.2 External Water Pump

The external pump, unlike the submersible pump, is placed outside the water reservoir and pulls water through tubing. One of the main advantages of an external pump is easier maintenance, as it is more accessible for cleaning and replacement without needing to be submerged. It is also more durable since it is not constantly exposed to water, which helps prevent motor damage. However, external pumps generally consume more power, require additional tubing for water intake, and take up more space, making them less ideal for our compact plant pot design. Additionally, they tend to be noisier and can experience airlocks, which may require extra components like check valves to maintain consistent water flow. While an external pump could work in larger-scale applications, it is not the best fit for our indoor plant pot, where space efficiency, quiet operation, and low power consumption are the main priorities.

Water pump type features comparison table

Feature	Submersible Pump	External Pump
Placement	Inside the water reservoir	Outside the water reservoir
Noise Level	Low	high
Space requirement	Compact	Require extra space for installation
Power Consumption	Low (Energy efficient)	Higher power draw
Maintenance	Harder to access, require filter to prevent clogging	Easy to access and replace
Durability	Can degrade over time due to water exposure	More durable as it stay dry
Risk of Airlocks	No airlocks	Possible airlocks, require check valves
Best use Case	Compact for our project with built in reservoirs	Larger scale system like outdoor plant

3.5.2 Water pump Selection

Based on the research of submersible and external pumps. We decided to choose a 5V mini submersive water pump since it achieves our goal of low power consumption, more compact, and quiet operation since our project aims for indoor use.

The choice of a 5V mini submersible water pump for our project is crucial in ensuring the efficiency and functionality of the automatic watering system. Submersible pumps are designed to operate fully underwater, making them more compact, quieter, and ideal for small, enclosed systems like our Biosense Pot project. The primary advantage of this pump type is its low power consumption, which aligns with our goal of creating an energy-efficient system that can be powered by a 5V solar panel and a 3.7V battery. By keeping the system compact, we can ensure the water pump integrates seamlessly within the confined space of the plant pot without compromising the design or functionality.

In addition, the 5V mini submersible pump's quiet operation is particularly suited for indoor environments, where noise levels need to be kept to a minimum. Since our project targets indoor plant care, the low noise is an essential feature to prevent any disturbance in the living space. Furthermore, the pump's low power draw ensures that it will not overtax the solar-powered system, making it a sustainable choice. Overall, the 5V mini submersible water pump is compatible with the constraints of our project, providing an efficient, reliable, and environmentally friendly solution for automated watering.

The 5V submersible water pump is a critical component of our automatic watering system, ensuring efficient water distribution for the indoor plants in our BioSensePot project. This pump is specifically designed for low-power applications and operates at a nominal voltage of 5V, making it highly compatible with our ESP32-WROOM microcontroller and solar-powered system. Its small form factor allows it to be fully submerged in the built-in water reservoir, eliminating the need for excessive tubing and reducing space constraints. The pump is designed to operate quietly, which is essential for indoor applications where noise reduction is a priority.

In terms of power specifications, the 5V submersible pump typically operates at a current draw of around 100mA to 300mA, depending on the flow rate and resistance in the water lines. This makes it a highly efficient option for our project, as it minimizes power consumption while ensuring adequate water flow. Given our energy management strategy, which includes a 5V solar panel and a 3.7V Li-ion rechargeable battery, the pump's low power draw allows for optimal integration. By employing a boost converter, we can efficiently step up the 3.7V from the battery to 5V, ensuring stable operation. The microcontroller can regulate the pump's activation based on real-time soil moisture data, effectively conserving both water and energy.

Additionally, the waterproofing characteristics of the pump are an important consideration for long-term reliability. Many 5V submersible pumps come with an Ingress Protection (IP) rating of IP67, meaning they are fully protected against dust and can withstand temporary immersion in water. This level of protection is essential for preventing damage and ensuring durability in an enclosed reservoir environment. With the combination of its waterproof design, low power consumption, and seamless compatibility with our BioSensePot system, this pump is the ideal choice for our smart indoor plant watering solution.

The specification of the 5V mini pump submersible including:

Feature of the subversive 5V water pump	Specification
Operating Voltage	5V DC
Current Draw	100mA-300mA
Power Consumption	0.5W-1.5W
Flow Rate	80-120L/H

Maximum Lift Height	0.5-1.2m
Waterproof Rating	IP67
Dimensions	~35mmx25mm
Noise Level	Low (<35dB)

3.5.3 Water Level Sensor

Water Level Sensor is crucial to include in an automatic watering system to monitor the water level in the reservoir and ensure the watering does not overflow or dryness. The role of the water level sensor is to send a signal to stop the pump to prevent running dry. It also prevents overflows by signaling the system to stop adding water in the reservoir. Our project also sends the data and notification to alert users for low water levels or overflow. There are different water level sensors used in the industry. We will compare and select the different purposes, features, advantages and disadvantages of various types of water level sensors.

3.5.3.1 Capacitive Water Level Sensor – DFRobot Capacitive Sensor

The capacitive water level sensor can be used by measuring the changes in capacitance caused by the rise and fall of water. This sensor has high accuracy, reliability, and does not require direct connection with the water, reducing the risk of corrosion which means it requires less maintenance [110]. It is commonly used in applications where durability and long-term stability are important. In our project, the capacitive sensor is an attractive option due to its ability to provide precise water level measurements without direct exposure to the liquid, making it a low maintenance solution [110]. However, it may require periodic calibration to maintain accuracy, and the cost is generally higher compared to other sensor types.

The capacitive water level sensor eliminates direct contact with liquid, making it resistant to corrosion and mineral buildup. By detecting changes in capacitance caused by water presence, it provides a reliable, non-intrusive measurement solution [110]. This characteristic makes it ideal for applications where long-term stability and minimal maintenance are required. The sensor operates within a 3.3V to 5.5V range, allowing seamless integration with ESP32 without additional circuitry. Since it outputs an analog signal, it enables continuous monitoring of water levels rather than discrete threshold detection. However, capacitive sensors require precise calibration to account for variations in container material and thickness. External factors such as humidity and environmental interference may introduce minor fluctuations in readings. Despite these constraints, the sensor's compact size and waterproof design allow for flexible placement. Its ability to function without physical water contact minimizes degradation over time, making it a superior choice for non-invasive water level detection in the BioSensePot [110].

3.5.3.2 Resistive Water Level Sensor – DFRobot Gravity Analog Water Sensor

The resistive water level sensor functions by measuring the electrical resistance between two probes placed at different heights in the water reservoir. When water is present, it completes the circuit, allowing the sensor to detect the water level [111]. This type of sensor is cost-effective and easy to implement, making it a common choice for simple water level monitoring systems. However, since it relies on direct contact with water, it is prone to corrosion over time, which may affect its accuracy and longevity [111]. Additionally, mineral buildup from water can lead to false readings, requiring regular maintenance. While it is a budget-friendly option, the potential maintenance challenges make it less suitable for our project, where long-term reliability is a priority.

The resistive water level sensor utilizes direct electrical contact with liquid to measure conductivity variations at different depths. This approach makes it highly responsive to changes in water level, providing immediate feedback on fluid presence [111]. Designed for low-power operation and featuring a 3.3V to 5V analog interface, it can be interfaced directly with ESP32 without requiring external components. Its flexible strip design allows for easy installation in confined spaces, making it a practical choice for compact smart plant systems like BioSensePot. Despite its affordability and accuracy, resistive sensors suffer from electrode corrosion over time, particularly in hard water environments with high mineral content. As the sensing elements degrade, measurement consistency can be compromised, requiring periodic maintenance [111]. Additionally, resistive-based sensing can be affected by impurities or waterborne debris, which may introduce temporary signal variations. While suitable for short-term and indoor applications, its long-term reliability depends on environmental conditions and maintenance frequency.

3.5.3.3 Float Switch Sensor – DEVMO Mini Indicator Vertical Water Level Sensor

The float switch sensor operates using a buoyant float that rises and falls with the water level, triggering a switch when the water reaches a predetermined height [112]. It is a simple, mechanical solution that requires minimal power, making it an energy-efficient choice. This sensor is widely used in applications where basic water level detection is sufficient. However, its mechanical nature makes it susceptible to wear and tear over time, and it may not provide continuous real-time monitoring as precisely as electronic sensors [112]. Additionally, float sensors can be affected by debris or biofilm buildup, potentially leading to malfunctions. While the float switch sensor is a low-cost and straightforward option, its limitations in accuracy and reliability make it less ideal for our automated plant pot design.

The float switch sensor provides a binary on/off signal, activating when water reaches a predefined level. This mechanical approach ensures robust and fail-safe operation, making it highly reliable for overflow protection or minimum water level detection [112]. The sensor consists of a buoyant element that rises with liquid and triggers an internal

switch when a threshold is met. With its compact 45mm form factor and waterproof casing, it can be easily integrated into small-scale hydroponic or irrigation systems. However, float switches are inherently limited in precision, as they can only indicate whether water is above or below a set point. Unlike capacitive or ultrasonic sensors, which provide continuous level data, a float switch is better suited for simple threshold-based automation rather than detailed measurement. Mechanical wear over time may also lead to switch sticking or failure in high-debris environments [112]. Nevertheless, its low power consumption and mechanical simplicity make it an efficient solution for applications that require basic liquid level detection with minimal electronics.

3.5.3.4 Ultrasonic Water Level Sensor – DFRobot URM09

The ultrasonic water level sensor works by emitting ultrasonic waves that reflect off the water surface, measuring the time it takes for the signal to return [113]. This allows for accurate, non-contact water level measurement, making it a highly reliable and maintenance-free option. It provides continuous monitoring and is not affected by corrosion or mineral buildup. However, ultrasonic sensors require a clear path between the sensor and the water surface, meaning placement must be carefully considered in the design [113]. They also tend to be more expensive and require more power compared to other sensors. Despite these drawbacks, the ultrasonic water level sensor is a strong candidate for our project due to its precision, durability, and minimal maintenance needs.

The URM09 Ultrasonic Sensor from DFRobot is engineered for rapid distance measurement and obstacle detection, making it suitable for applications like robotic navigation and vehicle reversing alerts [113]. Operating within a voltage range of 3.3V to 5.5V, it ensures compatibility with various controllers, including Arduino and Raspberry Pi. The sensor offers a measurement range from 2 cm to 500 cm, with a resolution of 1 cm and an accuracy of $\pm 1\%$. Its maximum measurement frequency reaches up to 50Hz, allowing for swift data acquisition. A notable feature of the URM09 is its built-in temperature compensation, which enhances measurement reliability across varying environmental conditions [113]. The sensor provides three selectable measurement ranges—150 cm, 300 cm, and 500 cm—enabling users to tailor the sensor's sensitivity and response time to specific application needs. Communication is facilitated via the I2C protocol, simplifying integration with microcontrollers. The sensor's compact dimensions (47mm x 22mm) further contribute to its versatility in space-constrained projects.

Water level sensor comparison table

Sensor Type	Model	Operating voltage	Interface	Measurement range	Blind zone
Capacitive	DFRobot Capacitive Sensor	3.3V - 5.5V	Analog	Varies	N/A
Resistive	DFRobot Analog Water Level Sensor	3.3V - 5V	Analog	Varies	N/A
Float Switch	DEVMO Mini Float Switch	Up to 100V DC	Digital	Point detection	N/A
Ultrasonic	DFRobot URM09	3.3V-5.5V	I2C	2cm-500cm	2 cm

3.5.4 Water level sensor selection

The selection of the DFRobot URM09 ultrasonic sensor for BioSensePot is driven by its non-contact measurement capability, ensuring long-term reliability in a moist environment without the risk of corrosion or sensor degradation. Unlike resistive and float switch sensors, which require direct interaction with water and are prone to wear over time, the URM09 operates using ultrasonic pulses, maintaining accuracy without physical exposure. With a measurement range of 2 cm to 500 cm and an I2C interface, it offers both high precision and efficient data communication, reducing the processing load on the ESP32. Its compact form factor and IP-rated waterproofing make it an ideal choice for integration into a confined yet sensor-dense system like BioSensePot.

Additionally, the URM09's adjustable sensitivity and noise-filtering features ensure consistent readings even in fluctuating environmental conditions. Traditional float switches provide only binary detection, while resistive sensors may suffer from inaccuracies due to impurities in water. In contrast, the URM09 delivers continuous, real-time depth measurement, allowing the system to optimize water usage dynamically rather than relying on predefined thresholds. Since BioSensePot prioritizes precision and automation, the URM09's ability to offer detailed water level data without maintenance concerns aligns perfectly with the project's goals, making it the most suitable choice among available sensing technologies.

3.6 Batteries

The battery selection is a key factor in ensuring that our project operates efficiently and reliably. Since our project involves multiple components such as sensors, a water pump, and a microcontroller, we need a power source that balances energy efficiency, lifespan, and safety. There are several battery types available, each with its own strengths and weaknesses. In this section, we will explore the key options and determine the best fit for our design

3.6.1 Lithium-ion (Li-on) batteries

Lithium-ion batteries are renowned for their high energy density, long cycle life, and lightweight design, making them the preferred choice for portable electronics and embedded systems [114]. Their ability to deliver stable voltage and high efficiency has led to widespread adoption across various industries. Since their market introduction in 1991, Li-ion batteries have seen significant improvements, with volumetric energy density tripling and costs dropping tenfold over the past three decades [114].

However, Li-ion batteries require protection circuits to prevent overcharging and deep discharge, which can lead to reduced battery life or safety risks [114]. Manufacturing defects or physical damage can cause internal short circuits, leading to thermal runaway and potential fires [115]. Despite these risks, advancements in battery management systems and manufacturing processes have enhanced the safety and reliability of Li-ion batteries, solidifying their role in modern technology [114].

3.6.2 Lithium Cobalt Oxide (LCo) Batteries

Lithium cobalt oxide batteries are known for their high energy density and lightweight structure, making them suitable for compact applications like smartphones and laptops [116]. Their ability to deliver high voltage and stable performance has made them a staple in consumer electronics. The cobalt-based cathode material contributes to the battery's high energy capacity, allowing devices to operate longer between charges [116].

However, LCo batteries tend to have a shorter lifespan and are prone to overheating, which poses potential safety risks [116]. The thermal instability of cobalt oxide can lead to thermal runaway under certain conditions, necessitating robust battery management systems to mitigate these risks. Additionally, the high cost and ethical concerns associated with cobalt mining have prompted research into alternative materials, aiming to develop safer and more sustainable battery technologies [116].

3.6.3 Nickel Cadmium (Ni-Cd) Batteries:

Nickel-cadmium batteries are durable and long-lasting, capable of handling extreme temperatures and high discharge rates [117]. They have a long cycle life and can withstand frequent charging and discharging, making them suitable for applications requiring reliable power over extended periods. Ni-Cd batteries also maintain a

relatively constant voltage during discharge, which is beneficial for certain electronic devices [117].

However, Ni-Cd batteries suffer from the memory effect, where repeated partial discharges can cause the battery to "remember" a lower capacity, leading to reduced performance over time [117]. Additionally, cadmium is a toxic heavy metal, posing significant environmental concerns during disposal. The European Union has banned the sale of consumer Ni-Cd batteries, except for specific applications, due to these environmental and health risks [117].

3.6.4 Lithium Polymer (Li-Po) Batteries

Lithium polymer batteries are a variation of Li-ion technology that use a flexible, lightweight design, making them ideal for projects where space is limited [118]. They provide high discharge rates and can be manufactured in various shapes and sizes, offering versatility in design. Li-Po batteries are commonly used in applications like drones, radio-controlled vehicles, and portable electronics, where weight and form factor are critical considerations [118].

However, Li-Po batteries are more sensitive to overcharging and physical damage, requiring careful handling and robust protection circuits [118]. Improper charging or mechanical stress can lead to swelling, reduced performance, or even safety hazards. Despite these risks, their lightweight nature and efficiency make them a promising candidate for applications demanding compact and high-performance energy storage solutions [118].

Battery Comparison table

Battery Type	Energy Density (Wh/kg)	Cycle Life	Self Discharge Rate (% per month)	Operating temperature Range (C)
Li-ion	150-200	500-1500	Around 5-10%	-20 to 60
Lithium cobalt Oxide (LCo)	150-200	500	5-10%	0 to 40
Nickel Cadmium(Ni-Cd)	40-60	1000-2000	10%	-20 to 60

Lithium Polymer	100-158	500	0.3%	-20 to 60
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3.6.5 Battery Selection

After analyzing various battery types, we have chosen Lithium-ion (Li-ion) batteries for our senior design project. Li-ion batteries offer the best balance between high energy density, long lifespan, and efficiency, making them ideal for our project. Their ability to deliver consistent power output ensures that all components, including sensors and the water pump, function reliably. Additionally, Li-ion batteries have a lower self-discharge rate compared to other types, ensuring that our system remains powered for longer durations. While they require proper charge management, their overall advantages make them the best choice for our project. This selection ensures our smart plant system remains efficient, reliable, and sustainable, aligning with our goal of building a practical and long-lasting solution.

3.7 Dynamic Lighting System

The Dynamic Lighting System is a Bio-Sense Pot sub-system responsible for monitoring and dynamically controlling the system's lighting environment that the plant is exposed to, both from ambient sources and from the system's own grow lights. Unlike traditional horticultural systems with fixed lighting schedules and outputs, this system is designed to actively adjust light intensity and spectral composition in real time based on sensor feedback. By combining grow lights, light intensity sensors, spectrometers, and light diffusers into a unified feedback loop, the system can optimize lighting conditions throughout the day and compensate for changing ambient light and plant growth stages. Each of the sub-systems plays a dedicated role, grow lights serve as the controllable light source, intensity sensors provide low power real-time feedback, spectrometers verify internal spectral content and inform the system on ambient spectral content, and diffusers condition the optical inputs and outputs for consistent behavior. This section explores the design, selection, and integration of each of these components, as well as the constraints that shaped their development.

3.7.1 LED Grow Light

The LED grow light functions as the most critical sub-system in the product's dynamic lighting functionality. The grow light's primary function is to act as a complimentary light source to whatever ambient light is already incoming on the plant. This sub-system works in conjunction with the light intensity and spectral sensors, informing the system on how to adjust the grow lights, and achieving the desired dynamic system that allows for such optimized plant growth. Unlike fixed-output lighting systems, the grow lights in the Bio-Sense Pot are designed to control both light intensity and spectral composition independent of each other, with the ability to adjust red and blue light ratios dynamically.

in response to sensor feedback. This allows the system to deliver specific light conditions based upon the level of light that a plant generally needs, and the life stages of a plant, thus effectively supporting photosynthesis and healthy plant development for a variety of plants. The grow lights also serve as the primary optical actuator within the system's feedback loop, responding to real-time measurements of ambient conditions that are collected from the system's optical sensors. Even light distribution from the grow light's output will be obtained through the use of a light diffuser, this will be covered in the light diffuser section. The capabilities of the grow lights must be balanced with the project's physical and technical constraints—including a limited implementation space less than 8 square inches, thermal dissipation concerns, and power delivery challenges—all of which have shaped the choice of components and the overall design strategy.

3.7.1.1 Design Requirements and Constraints

The grow light sub-system is subject to several design requirements and constraints that directly impact the performance, integration, and long-term feasibility of any light source selected. The system must be capable of independently controlling both output intensity and spectral composition. This level of control is critical to support a variety of plant types and growth stages, each requiring different lighting conditions for optimal development. Studies have shown that plants exhibit varying photosynthetic responses to light intensity, with many species experiencing a saturation point beyond which additional light has diminishing or even harmful effects. This is known as the light saturation point [15]. Similarly, each plant species has a minimum light intensity threshold, below which photosynthesis is insufficient for growth. These upper and lower limits define the usable intensity range for different plants, allowing species to be grouped by their general light level needs [16].

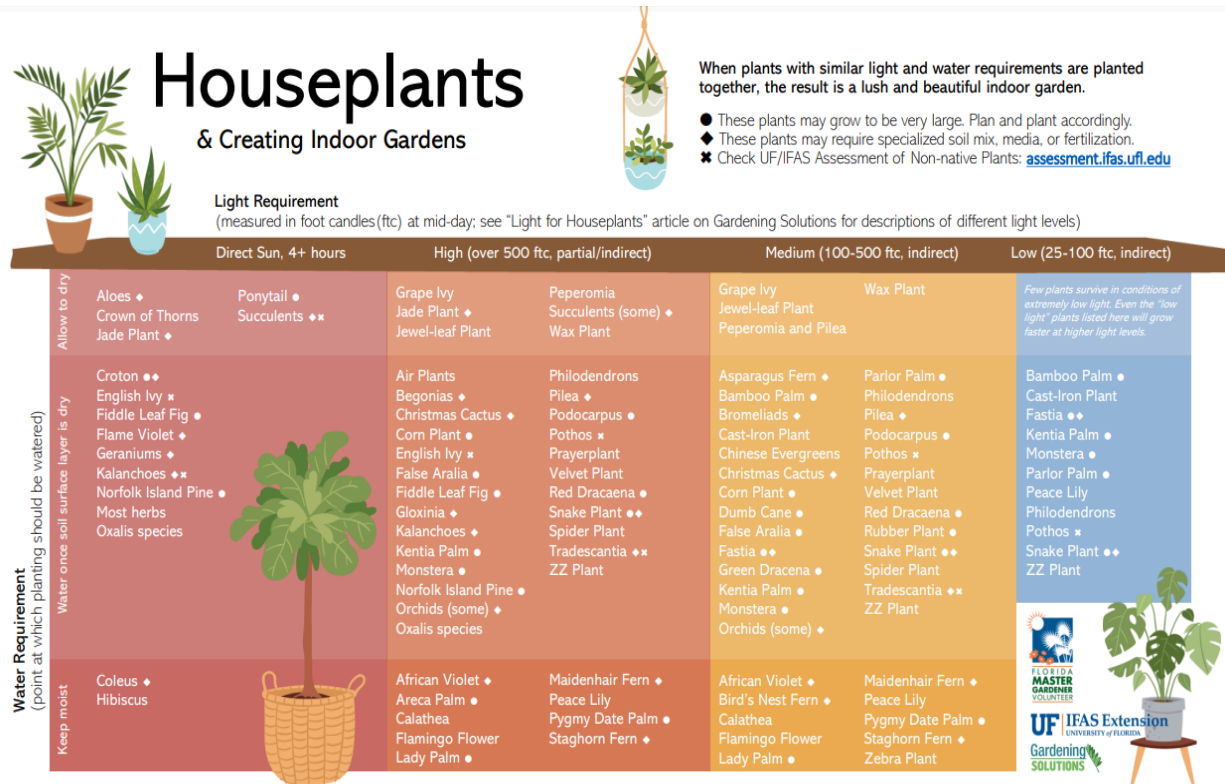


Figure 19: Diagram illustrating plants pertaining to different light level categories (measured in ftc) and what kind of watering they would need. Sourced from University of Florida IFAS.

It should be noted that while the above figure measures light intensity in foot-candles, relating light intensity to the brightness of X number of candles one foot away. For the sake of cohesion with the sensors and testing equipment that will be used, our project will measure light in Lux. Lux is a unit of illuminance equivalent to one lumen per square meter, and ftc is a unit of illuminance equivalent to one lumen per square foot, therefore ftc can be converted to lux with the equation

$$\text{Lux} = \text{ftc} * 10.764$$

Equation 1: ftc to lux conversion

However, lux alone is not the most relevant measure of light for plant growth. Lux is weighted toward human visual sensitivity, overemphasizing green light, which plants use less efficiently. Instead, Photosynthetic Photon Flux Density (PPFD) provides a more accurate measure for plant growth, as it quantifies the number of photosynthetically active photons (within 400–700 nm) that reach a given area per second, measured in $\mu\text{mol}/\text{m}^2/\text{s}$. PPFD is more directly linked to plant health because it focuses on the actual usable light energy driving photosynthesis. For this reason, while lux is used in sensor calibration and general system measurements, PPFD will be used when discussing biological effectiveness and determining whether the light provided supports proper plant growth.

In addition to the intensity of incoming light, the spectral composition of incoming light also has a significant effect on plant growth. A specific range of wavelengths has been identified as more biologically effective for plant development than others; particularly light ranging from red light (around 660 nm), which supports stem elongation and flowering, and blue light (around 450 nm), which regulates leaf growth and vegetative structure. These two spectral regions form the basis of Photosynthetically Active Radiation (PAR for short) [15].

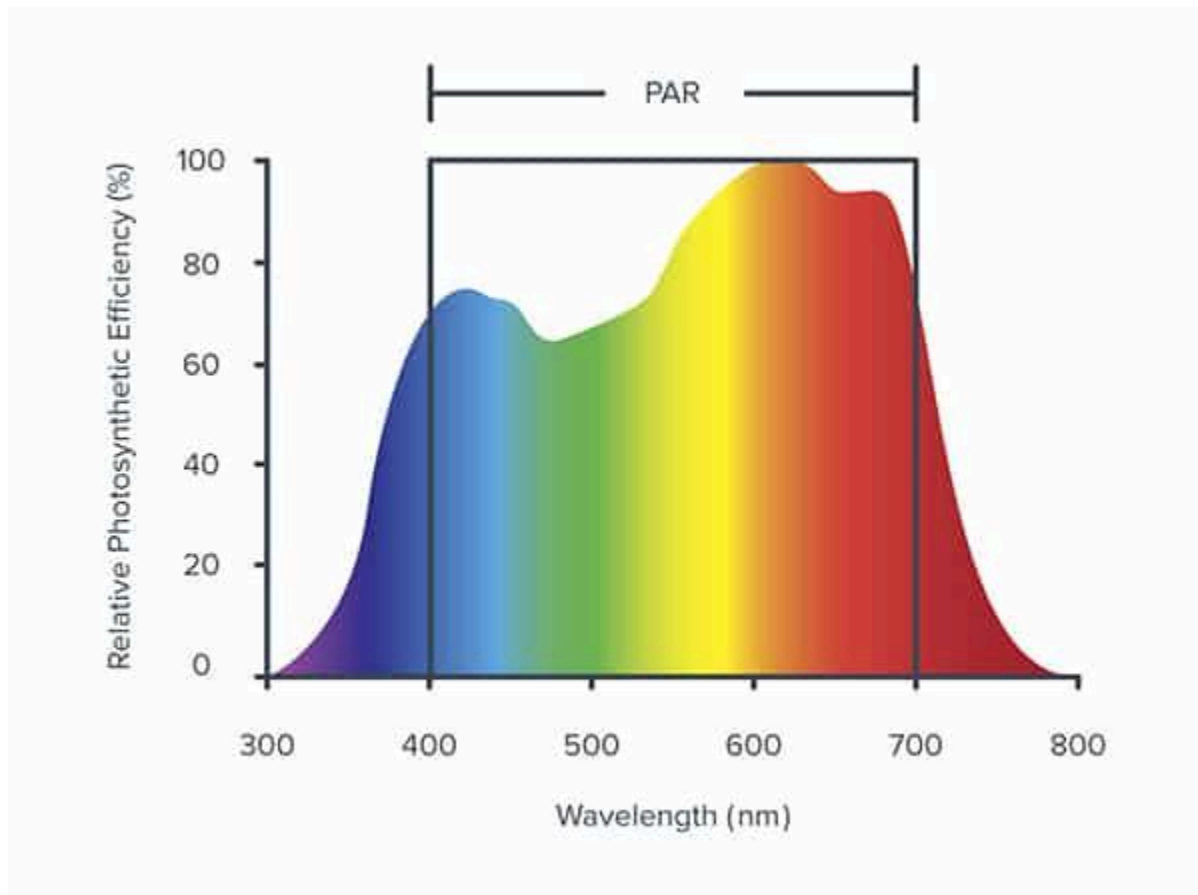


Figure 20: Graph demonstrating Photosynthetic Efficiency Versus Wavelength of Light. Indicates the range of wavelengths, the PAR, that most positively affect Photosynthesis efficiency. (Fluence 2025)

Each of these colors of visible light has its own particular focus area for plant growth, with red light relating to seed germination, stem elongation, and flowering, while blue light affects leaf expansion/thickness, and stomatal regulation [19]. Grow light systems can be designed to combine these components dynamically, and at different ratios to each other, to allow for more precise positive input into plant health and growth for different stages in a plant's life-cycle. Studies have been done on red/blue light ratio for a variety of specific plants, and a general pattern of ratios for various growth stages has emerged [20, 21].

Growth Stage	Red:Blue Light Ratio	Effects
Seedling Development	1:1	Promotes balanced growth and strong root development.
Vegetative Growth	3:1 to 5:1	Enhances leaf expansion and stem elongation
Flowering and Fruiting	5:1 to 7:1	Stimulates flowering, bud formation, and fruit development.

Figure 21: Table describes the different red:blue light ratios applicable to different stages in a plant's growth and the effects that that ratio has.

As the light intensity and spectral composition both are key system variables, each affecting plant-growth independently, it is important that the light intensity and spectral composition can be controlled separately and independently of each other.

The light source must also be able to respond to feedback collected from sensors. This necessitates a light source that can communicate with the system and properly receive information from the system sensors in order to adjust accordingly, ensuring correct lighting (both in intensity and spectral composition). Therefore the light source must be able to communicate with the system's onboard microcontroller, the ESP32 which operates at 3.3V - 5V logic. If the light source requires a different logic level, additional signal shifting may be necessary to maintain compatibility and avoid signal degradation.

Physical constraints also play a crucial role in directing the system's design and limiting implementation. The grow light must be mounted within a roughly 8-inch by 8-inch square area (consistent with the upper pot platform). This restricted area is further hindered by probable additional electronic components required by the system (wiring, solar panel components, etc...). This restricted area also limits the number and size of components that can be placed above the plant without negatively affecting other system functions or overall system stability.

High output lighting introduces power delivery concerns, particularly when long light strips or arrays are used. Without proper power injection and distribution, voltage drops can occur, leading to inconsistent output that compromises the plant's ability to receive uniform lighting. In addition, higher power light sources operating in confined spaces can lead to thermal buildup, requiring passive heat-sinking or similar thermal mitigation strategies. Excessive heat may not just reduce component lifespan, but also alter the temperature around the plant, introducing stress that can affect growth patterns.

Finally, since the system is expected to operate in response to real-time sensor data, any light source must be capable of seamless integration into the system's feedback loop without introducing significant latency or communication delays. Plants respond to cumulative light exposure over time, and while minor delays are tolerable, prolonged mismatches between sensor readings and light adjustments can result in under/over exposure. These constraints serve as a baseline for evaluating light sources and eliminate any options that cannot meet the physical, electrical, or functional demands of the design.

Category	Target/Constraint	Likely Implementation Method
Spectral Control	Adjustable Red:Blue ratio	Individually addressable RGB LEDs
Brightness Control	Dynamic control ranging from ~0% to 100% output intensity	Software via ESP32
Logic Compatibility	3.3V - 5V control via ESP32	Level shifter to out of range values and possible level shifter for 5V
Max Physical Size	Takes up area < 8" x 8"	Proper cable/space management
Power Distribution	No significant voltage drop or power draw	Power injection at multiple points and reduced lighting intensity capability
Thermal Output	Prevent light source and nearby system components from overheating	Heat-sink (Likely aluminum backing)
Sensor Integration	Real-time sensor feedback	I ² C-based sensors (TSL2591, AS7341)

Figure 22: Table describing the various requirements and constraints inherent to light source selection.

3.7.1.2 Types of Light Sources for Controlled Lighting

Controlled lighting systems for commercial horticulture products rely on the ability to modulate both light intensity and spectral composition with precision. Several light source technologies have been employed to meet these demands, including fluorescent lamps, high-pressure sodium (HPS) lamps, and more recently, light-emitting diodes (LEDs). While traditional sources like HPS lamps and fluorescent tubes have been used in large-scale agriculture, they fail to apply to compact consumer applications due to their bulkiness, fixed spectral outputs, and poor energy efficiency [22]. Fluorescent lamps can offer some spectral tuning through phosphor blends, but these modifications are not easily adjusted after installation and typically result in low-intensity light that limits growth stimulation [23].

LEDs offer a compact and energy-efficient solution capable of delivering specified output with a high degree of control over spectral composition and intensity. Unlike the previously mentioned light sources, LEDs are inherently modular and therefore allow for tuning via the ESP32. This makes them well suited for our system. By combining red, green, and blue emitters into configurable arrangements, multispectral LED modules can approximate a wide range of light compositions, therefore supporting the specific growth stages discussed earlier. While they might not match the high intensity output of the fixed-spectrum, commercial, horticultural lights, their modularity and reduced power makes them especially useful in systems like ours with physical or thermal constraints. For the Bio-Sense Pot, where space is limited and dynamic behavior is key, LEDs provide the desired balance between lighting control, efficiency, and ease of integration with our system.

Feature / Metric	Fluorescent Lamps	HPS Lamps	High-Power LEDs	Addressable RGB LED Strips (WS2812B, Selected)
Spectral Range (nm)	400–700	550–650	380–750 (model dependent)	450 (Blue), 520 (Green), 630 (Red) per channel
Power Consumption (per ft ²)	20–40 W	40–60 W	15–35 W	7–14 W (based on density)
PAR Output (μmol/m ² /s at 12")	~80–150	~150–200	200–400	~100–150 (RGB combined)

Thermal Output (Watts of heat)	Moderate (~50% radiant loss)	High (~70% radiant loss)	High (~60–70% efficient)	Low (~80% electrical efficiency)
Dimming / Control Method	Analog dimmer (optional)	Requires ballast dimming	PWM / Analog via driver	Digital via ESP32 (1-wire data line)
Lifespan (Hours)	10,000–20,000	10,000–24,000	25,000–50,000	50,000+
Size/Form Factor	Bulky	Large reflector fixtures	Panels/strips, requires heatsinking	Flexible 10 mm-wide strip
Control System Compatibility	Low (manual only)	Very low	Medium (requires external driver)	High (direct ESP32 integration)
Cost per ft² Coverage (Estimate)	\$5–\$10	\$10–\$20	\$25–\$40	\$8–\$12
Best Use Case	Budget hobby setups	Greenhouses, industrial farms	High-yield growth setups	Smart, sensor-driven indoor systems

Figure 23: Table comparing the different types of light sources for the grow light system.

3.7.1.3 Component Evaluation and Selection

The final selection of the grow light source is shaped by the weighing of several factors such as ease of integration, achievable light output, and compatibility with the Bio-Sense Pot's electrical system. Two candidates were considered within the category of LED lights sources: high-power LEDs and addressable RGB LED strips. Both were evaluated for their ability to meet system needs under the requirements, constraints, and desired properties all mentioned previously.

High-power LEDs offer more than sufficient intensity and relative efficiency when looking at single instances of LEDs, producing anywhere from 60 to 100 $\mu\text{mol/s}$ per watt depending on driver and thermal configuration. The units of $\mu\text{mol/s}$ per watt is called Photosynthetic Photon Flux Density (PPFD), and it is a measure of the number of photosynthetically active photons that reach a square meter per second, spanning 400nm to 700nm. This unit of measurement is particularly useful for plants because it quantifies the light energy actually usable for photosynthesis [24]. The high-power LEDs are commonly used in commercial greenhouse applications, where large output of photons is the primary concern. However, their implementation demands additional

circuitry, including constant current drivers and MOSFET based control logic. Physically, they would also require individual wiring and mounting for each individual LED, as well as active or passive thermal management that is more effective or involved than for other LEDs, likely involving heat sinks or aluminum mounting panels. While their performance is attractive for a plant growing project, their installation complexity, especially in a compact system like the Bio-Sense Pot, make them impractical. In addition, their limited spectral flexibility and lack of real-time tunability conflicted with the project's dynamic lighting goals.

RGB LED strips, on the other hand, offer a much more modular and less technologically involved option. The strips allow control of individual diodes through a single data line, supporting dynamic adjustments to spectral composition and brightness without extensive wiring. Operating at 5V and communicating over a protocol compatible with the ESP32 system, these LEDs are simple to integrate from both a hardware and software perspective. Their intensity output, while significantly lower than that of high-power horticultural LEDs, can still support low- to moderate-light plants when used in effective quantities. When configured densely, such as with ~100 to 200 LEDs in an 8-inch-square area, the resulting PPFD is sufficient to drive meaningful photosynthetic activity for even high light-level plant life. This trade-off—lower raw output but greater control and ease of integration—aligns much better with our project goals.

Going a step further, RGB LED strips can be separated into the categories of addressable and non-addressable strips. Addressable strips allow for the enabling of each diode to be individually programmed. This allows us full pixel-level control of color and intensity, which is essential for our sensor-driven feedback system. Meanwhile, the non-addressable RGB LED strips operate with either a shared control signal or none at all, meaning all LEDs on the strip behave identically and don't allow for easy user modification. This restricts the system to static brightness levels or simple color mixing spanning the whole strip at once. As a result of the lack of capability for pixel-level variation, they cannot support dynamic lighting behaviors

Given these considerations, addressable RGB LED strips were selected as the grow light source. Their compatibility with the ESP32 system, ease of physical mounting, and ability to support dynamic lighting behaviors made them the only viable option for balancing system complexity, and nuanced lighting control. In particular, the WS2812B LED strip was chosen for its low cost, widespread use in hobby electronics, and its ability to meet nearly all of the Bio-Sense Pot's grow light requirements, being only limited by output intensity needing to be compensated with greater LED quantity, making it an effective choice for our system's lighting.

Component	PPFD Output	Power (W per ft²)	Control Method	Requires Driver?	Logic Compatibility	Form Factor	Cost Estimate (USD)

	($\mu\text{mol}/\text{m}^2$ /s @12")						
High-Power LEDs (1W–3W each)	200–400	15–35	PWM via MOSFET	Yes	3.3V signal requires interfacing	Individual LEDs + heatsink	\$25–\$40 per ft ²
Non-Addressable RGB LED Strips	60–100 (combined RGB)	10–20	Analog or shared PWM	Sometimes	Partial (limited tunability)	10 mm strip	\$5–\$10 per meter
WS2812B LED Strip (Selected)	~100–150 (combined RGB)	7–14	Digital (1-wire protocol)	No	Native 5V logic (ESP32 OK)	10 mm addressable strip	\$8–\$12 per meter
COB LED Array	300–600	20–50	PWM with external controller	Yes	Requires logic level shift	Integrated PCB/heatsink	\$30–\$60 per module

Figure 24: Table comparing the different types of LEDs.

3.7.2 Light Intensity Sensors

The light intensity sensors serve as the first part of the optical inputs for the Bio-Sense Pot's adaptive lighting system. Their role is to measure the amount of light the plant is receiving from both ambient sources and the system's grow lights, enabling real-time adjustments to maintain optimal lighting conditions. Unlike the spectrometers, which measure specific wavelength distributions, the light intensity sensors are solely focused on total illuminance. This distinction allows the system to use them for fast, low-power feedback to regulate light output without unnecessary complexity or computation.

Two distinct light intensity sensors are employed in the system. The external sensor is positioned to measure incoming ambient light, allowing the system to determine how much supplemental lighting is needed. In cases of sufficient natural light, this sensor enables the system to reduce the grow light's output, thereby conserving power and avoiding exceeding the plant's light saturation threshold. The internal sensor, located beneath the grow lights and above the plant, monitors the actual output of the grow light array. Because the LEDs cannot self-report intensity and the diffuser alters light transmission, this internal sensor ensures that light delivery to the plant matches calculated targets. Both sensors contribute to the system's optical feedback loop by continuously informing the grow light behavior, balancing the plant's needs with system efficiency.

As with the other optical sub-systems, the light sensors are subject to several constraints. These include limited physical mounting space, proximity to heat-generating components, and the need for compatibility with the ESP32's 3.3V - 5V, I²C, communication interface. The sensors must also offer a wide dynamic range to remain accurate in both high and low level lighting conditions, as well as avoid saturation under direct grow light exposure.

3.7.2.1 Design Requirements and Constraints

The light sensor sub-system is shaped by a set of technical requirements and physical constraints that directly impact the sensors that can be used and how they are implemented. As a central part of the system's optical feedback loop, these sensors must provide accurate, live, measurements of light intensity across a satisfactory range of conditions, from direct sunlight to dim, indoor, lighting environments. Both the external and internal sensors must be capable of detecting light levels relevant to plant growth, particularly around known minimum and maximum light thresholds, including the light saturation point, beyond which additional light becomes ineffective or harmful to the plant [15].

Because the Bio-Sense Pot is designed to operate in indoor and outdoor lighting (low intensity to high intensity), the sensors must feature a wide dynamic range while avoiding saturation, particularly under the intense artificial lighting that could result from the grow lights operating at higher outputs. The internal sensor must also account for the lost light intensity caused by the light diffuser and its transmission percentage, mounted between the LEDs and the plant. This requires the sensor to remain responsive even under slightly filtered conditions. In both cases, sensors must report in Lux or equivalent, since Lux is the primary unit used for intensity comparison across the system.

From an electrical perspective, both sensors must operate on a 3.3V – 5V logic level and communicate with the ESP32 using the I²C protocol. This ensures compatibility with the system's microcontroller and minimizes the need for additional logic-level shifting or signal conditioning. The sensors should also feature fast response times and minimal power draw to support real-time feedback and maintain energy efficiency.

Constraints caused by physical space are another key limitation. The internal sensor must be positioned at a point directly beneath the grow lights, while avoiding obstruction of the light path or interference from other components or the plant itself. The external sensor must be placed in a location that receives unobstructed ambient light but avoids exposure to reflected light from the grow lights, which could otherwise skew readings. Both sensors must be mounted securely in a way that maintains consistent orientation and exposure throughout the system's operation. The internal sensor, placed beneath the grow lights and light diffuser, is particularly susceptible to indirect reflections and off-axis glare from the surrounding enclosure. These stray inputs can lead to inaccurate readings that misrepresent the actual light reaching the plant, thus compromising the accuracy of our dynamic system. To mitigate this, a non-reflective baffle can be designed around the internal sensor to limit its field of view and block unwanted reflections, helping to ensure it only captures light passing through the main optical path from the grow lights. The external sensor, which measures ambient light outside the grow light's direct field, faces a different problem: it must respond to a wide range of lighting conditions, including sunlight, indoor lighting, and shade, while avoiding sharp spikes or directional bias. To help normalize its input and provide more consistent readings regardless of light angle or source type, a glass diffuser is positioned above the sensor. This diffuser softens incoming light and simulates an averaged exposure, improving the accuracy of ambient light intensity measurements and reducing over-response to direct light beams. This doesn't necessarily solve the problem of normalized light input all together though, to do that we would need multiple ambient light intensity sensors. For now we will have to further mitigate this problem by directing the user to face the Bio-Sense Pot in a certain direction or position relative to where incoming ambient light may be expected from.

Category	Requirement / Constraint	Likely Implementation Method
Measurement Range	Must detect intensity across a wide dynamic range (dim indoor light to full sunlight)	Use high dynamic range sensors (e.g., TSL2591, VEML7700)
Light Filtering	Internal sensor must compensate for light loss caused by the diffuser's transmission	Calibrate output against expected loss; adjust light output accordingly
Stray Light Control	Internal sensor must reject off-axis reflections to preserve reading accuracy	Add non-reflective baffle or shroud to limit field of view
Angle Normalization	External sensor must reduce directional bias	Add glass diffuser to average input over sensor

	from angled ambient light	surface
Data Output Format	Report intensity in Lux or equivalent units for feedback control	Use sensors with native Lux readout or convert from raw counts
Communication	I ² C protocol required for ESP32 compatibility	Select sensors with built-in I ² C support
Voltage Range	Operates on 3.3V – 5V logic to match ESP32 microcontroller	No level shifting required; direct wiring to ESP32 I ² C bus
Response Time	Must be fast enough for real-time system adjustments	Select sensors with <100ms update rate
Power Consumption	Should be low to help support system energy goals	Use low-power sensor modes; enable sleep between readings
Physical Mounting	Internal: avoid blocking plant light; External: avoid LED reflections	Internal mounted below diffuser; external placed in open-air (Ideally facing light)

Figure 25: Table listing the design requirements and constraints relating to the system's light intensity sensors

3.7.2.2 Types of Light Sensors

A few types of light intensity sensors were considered for use in the Bio-Sense Pot. These sensors differ in how they detect and report light levels, as well as in their dynamic range, interface requirements, and suitability for integration in a compact, feedback-driven system like ours.

Photodiode-based sensors are frequently used in light measurement applications. They offer high-speed response, low power consumption, and good spectral coverage, however, many of these sensors require analog readouts and external amplification circuitry, which increases implementation complexity and adds to PCB layout constraints. These sensors also require post-processing to convert raw signals into Lux or similar units, making them less ideal than sensors that automatically output a standardized Lux reading [25].

Basic LDR (light dependent resistor) modules offer low-cost ambient light detection but suffer from poor precision, slow response time, and non-linear output. LDRs also lack integrated digital communication protocols, limiting their ability to support a feedback system like ours. Due to their low resolution and limited accuracy, they are not suitable for applications requiring real-time adjustments or sensitivity to plant-specific thresholds [26].

Integrated digital light sensors, such as the TSL2591 and VEML7700, combine a photodiode array with onboard ADCs and I²C communication. These sensors offer high resolution, low power draw, and built-in Lux conversion, making them well-suited for embedded applications like the Bio-Sense Pot. Many models include built-in gain control and dual-channel sensing (visible and IR), allowing them to operate across a wide dynamic range without saturating under high-intensity light sources. Their compact form factor and low-profile integration makes them extremely favorable for placement both inside the pot (beneath the grow lights) and externally for ambient monitoring.

Given the need for fast, accurate, and low-complexity measurements, integrated digital sensors represent the most practical solution for this system. Their balance of sensitivity, electrical simplicity, and software compatibility made them the strongest candidates for further evaluation.

Technology	Output Type	Dynamic Range	Response Time	Spectral Sensitivity	Saturation Resistance	Microcontroller Integration	Power Consumption
Photodiode (Discrete)	Current (analog)	10 ⁴ –10 ⁶ :1 (circuit-dependent)	<10 ms	Filter-dependent	Low (saturates under strong light)	Requires amplifier circuit	~0.1 mA active
LDR (Photoresistor)	Resistance (analog)	~1,000:1	Slow (hundreds of ms)	Very broadband	Very Poor (easily saturated)	Simple voltage divider	Negligible (~μA range)

Phototransistor	Current (analog)	~1,000–10,000:1	<10 ms	Peaks at ~500–600 nm	Low (saturates under moderate light)	Simple but nonlinear	~0.1–1 mA active
Digital Lux Sensor (e.g., BH1750)	Digital (lux)	Up to 65,535 lux	~120 ms	Approx. visible range	Poor (saturates above 65k lux)	I ² C ready	0.12 mA active, 0.01 μ A power-down
High-Dynamic Digital Sensor (e.g., TSL2591)	Digital (lux + raw counts)	600,000,000:1	~100 ms	Dual diode for IR + visible split	Excellent (handles full sunlight)	Native multiple stages I ² C, gain	0.4 mA active, <5 μ A power-down

Figure 26: Table comparing the different types of light sensors.

3.7.2.3 Component Evaluation and Selection

The light intensity sensors selected for the Bio-Sense Pot are the TSL2591 and VEML7700 for the internal and ambient light sensors respectively. These two components meet the system's requirements for dynamic range, electrical compatibility, and form factor. These sensors are responsible for measuring both ambient and grow light intensity to support real-time lighting adjustments. To fulfill their role in the feedback system, the selected sensors needed to feature high sensitivity, fast response, native Lux output, and seamless integration with the ESP32 through I²C.

The TSL2591, used internally, was chosen for its extremely high dynamic range of up to 600 million:1, detecting extremely low-level light inputs, and handling high-intensity inputs without saturating. This makes it particularly well-suited for placement beneath the grow lights and diffuser, where reflected light and variable transmission could otherwise compromise accuracy. Its low power draw and compact footprint also make it ideal for tight internal mounting.

The VEML7700, positioned externally, offers solid sensitivity in both indoor and outdoor ambient lighting conditions, with a simpler spectral response curve and built-in Lux

conversion. Its stable behavior in fluctuating natural light environments makes it an ideal choice for sensing ambient conditions and providing the system with critical ambient lighting data.

Other integrated digital light sensors were evaluated during the selection process but ultimately ruled out due to specific limitations. The BH1750, while popular in hobby electronics, has a much narrower dynamic range and tends to saturate under strong lighting, making it unsuitable for use near high-output grow lights. The LTR-559 and APDS-9960 were also considered but offer broader functionality (including proximity or gesture sensing) that introduced unnecessary overhead without improving intensity measurement accuracy. These added features also increased power consumption and code complexity. In addition, the TSL2561, a predecessor to the TSL2591, was ruled out due to its lower resolution and weaker performance under strong or mixed lighting conditions.

After evaluating multiple options, the TSL2591 and VEML7700 provided the best trade-off between accuracy, hardware simplicity, dynamic range, and responsiveness—all critical factors for enabling reliable light regulation in the Bio-Sense Pot.

Component	Dynamic Range	Saturation Point	Response Time	Output Format	Power Consumption	I ² C Interface	Spectral Sensitivity	Integration Notes	Approx. Cost
TSL2591 (Internal and external)	600,000:1	>88,000 lux (auto gain)	~100 ms	Lux + Raw Counts	0.4 mA active, <5 µA sleep	Yes	Dual photodiode (Visible + IR)	Native ESP32 compatibility, very high ceiling	\$5–\$7
VEML7700 (External formal)	120,000:1	~100,000 lux	~100 ms	Lux	0.17 mA active, 0.5 µA sleep	Yes	Visible spectrum, 500–650 nm peak	Clean I ² C integration, lower lux ceiling	\$3–\$6
BH1750	~1,000:1	~65,535 lux	~120 ms	Lux	0.12 mA active, 0.01 µA sleep	Yes	Visible only, ~560 nm peak	Easy to use but saturates under	\$3–\$5

								strong LED light	
TSL2561	~40,000:1	~40,000 lux	~100 ms	Lux + Raw Counts	0.6 mA active, <15 μ A sleep	Yes	Dual diode (IR + Full)	Legacy part, less precise than TSL2591	\$4–\$6
LTR-559	~100,000:1	~60,000 lux	~100 ms	Raw ADC	0.2 mA active, <1 μ A sleep	Yes	Visible + IR (not separately filtered)	Includes proximity sensing, not needed here	\$4–\$7

Figure 27: Table of digital light intensity sensor comparison.

3.7.3 Light Diffusers

Light diffusers play a key role in the Bio-Sense Pot by shaping how light is distributed across the external internal optical system components. Rather than focusing or redirecting light, a diffuser's function is to scatter incoming rays in order to create a more even distribution of light intensity across a surface or volume. Within the Bio-Sense Pot, diffusers are employed in two main locations: beneath the grow light array and above the external optical sensors. Though their roles differ, both applications are critical to ensuring accurate feedback and effective plant lighting.

The internal diffuser, placed directly beneath the grow lights, is used to evenly distribute artificial light across the surface of the plant. Without this component, light intensity would vary across the growing area, creating hotspots and uneven exposure that could hinder plant development or stress specific regions of the plant canopy. Uniform diffusion is particularly important in a dynamically controlled system where lighting levels and spectral ratios change in real time. The external diffuser, positioned above the system's optical sensors, serves a slightly different purpose. Its goal is to soften and average incoming ambient light from multiple angles. This reduces the likelihood of sharp directional spikes or glare from localized light sources—conditions that can compromise the reliability of light intensity or spectral data. By normalizing the input light field, the diffuser helps maintain more stable, consistent, and interpretable sensor outputs.

While both components fall under the same general category of diffusers, their optical demands and physical design constraints differ somewhat. The diffuser beneath the grow lights must prioritize transmission and spatial uniformity without significantly reducing light intensity. Meanwhile, the diffuser above the sensors must handle a broad range of angles and ambient conditions without introducing spectral distortion or excess attenuation. These differing requirements have led to the use of separate diffuser types, each selected to meet the specific needs of its subsystem.

3.7.3.1 Design Requirements and Constraints

The use of diffusers in the Bio-Sense Pot is shaped by the distinct optical and mechanical demands of the subsystems they support. Both internal and external diffusers must effectively scatter incoming light while avoiding undesirable trade-offs in transmission, uniformity, or integration complexity. The constraints governing their use differ depending on whether the diffuser is applied beneath the grow lights or above the optical sensors.

The internal diffuser, located between the grow lights and the plant, is responsible for evenly distributing artificial light across the plant canopy. This ensures uniform exposure regardless of the number or position of LEDs. Without this layer, plants may receive uneven intensity, leading to localized overexposure or insufficient illumination in certain regions. The diffuser must maintain high optical transmission, preferably above 80%, to avoid significant light losses that would require the system to compensate with increased LED output (The more compensation the system needs to make for the grow light diffuser, the more likely accuracy is to suffer). It must also fit within a constrained vertical space, its weight must be light enough that it won't sag if it's made of malleable material, and it must resist discoloration or warping under prolonged heat exposure from the LEDs. The external diffuser, placed above the ambient light intensity sensor and the external spectrometer input, is tasked with normalizing light from a wider range of incident angles than what would be available if the light diffuser was not present. This helps prevent skewed measurements caused by directional glare or sharp light transitions in natural environments. The diffuser must scatter light uniformly across the sensor surface while minimizing spectral distortion. It must also maintain consistent optical behavior under changing environmental conditions, including outdoor lighting and temperature variation. Mechanically, it should remain fixed in place without blocking airflow or interfering with surrounding sensor enclosures.

Both diffusers must be physically compatible with the system's housing and other optical elements, introducing minimal thickness and requiring no active alignment after installation. In each case, the diffuser's scattering profile, transmission percentage, and mounting method are critical to ensuring both accuracy and consistency within the optical feedback system.

3.7.3.2 Types of Diffusers

A variety of types of optical diffusers were considered for use in the Bio-Sense Pot, each offering different trade-offs in light transmission, angular scattering, material

thickness, and integration complexity. The diffusers fall into two broad categories: surface-treated glass or plastic diffusers, and bulk-diffusing polymer sheets. Each category presents different advantages depending on the needs of the subsystem.

Surface-treated glass diffusers, such as ground glass or etched glass, use microscopic surface roughness to scatter light. These diffusers offer high angular diffusion and are well-suited for applications where light is incoming from a variety of angles. They typically exhibit excellent optical consistency over time, especially in outdoor or mixed-light environments. However, their rigidity and fragility make them less ideal for internal mounting beneath the grow lights, where weight, vibration, and mechanical fit are more sensitive constraints especially given the size of the grow lights and the subsequent cost that would entail for a glass diffuser of similar size.

Plastic sheet diffusers, including acrylic and polycarbonate (PC) materials with embedded diffusion particles, offer improved impact resistance and lower weight. These materials can be molded or laser-cut to fit custom enclosures and are generally easier to integrate in embedded systems. However, their transmission efficiency can vary depending on thickness, pricing, and concentration of diffusion material; and lower-end options may introduce spectral bias or yellowing over time under heat exposure.

Diffusive films and light shaping films, such as lenticular or holographic diffusers, were also briefly considered. While these can offer highly tunable beam shaping and are commonly used in display backlighting, their optical behavior is highly directional and often dependent on precise alignment. Even if we could align them and integrate them into the system appropriately, they are often very expensive. For this reason, they were not selected, as the system requires more generalized spatial scattering rather than collimated or beam-shaped output, and we don't want to inflate system cost when a cheaper option could be more effective.

Based on these factors, surface-treated glass diffusers were determined to be the most appropriate choice for the external sensing components, where optical stability, uniformity, and spectral neutrality are essential to measurement accuracy. In addition to optical performance, several practical considerations contributed to this selection—specifically, the availability of small, commercially standardized glass diffusers, and their material stability when compared to plastic alternatives. These factors make glass diffusers better suited for precision measurements in the external light intensity sensor and spectrometer subsystems.

For the internal diffuser positioned beneath the grow lights, no final selection has been made. Due to the stricter requirements on thermal stability, transmission efficiency, and mechanical integration, further research and testing will be required to determine the most suitable option. Two primary categories remain under consideration: bulk-diffusing plastic sheets and treated acrylic panels, both of which offer potential advantages in spatial light distribution and ease of integration. Ongoing evaluation will focus on comparing their transmission properties, heat resistance, and compatibility with the grow light geometry to guide the final selection in future development stages.

Diffuser Type	Transmission (%)	Scattering Angle	Material Thickness	Thermal Stability	Spectral Uniformity	Estimated Cost (per unit)	Best Use Case
600 Grit Ground Glass	~93%	Wide, uniform	~1.1–2.0 mm	Excellent (glass, inert)	Neutral across visible range	~\$10–\$15	External diffuser (sensor/spectrometer)
220 Grit Ground Glass	~70–75%	High scatter, coarse	~1.5–2.5 mm	Excellent	Slight spectral bias (blue loss)	~\$12–\$18	External use with strong angle averaging
Opal Acrylic Panel	~50–65%	Strong wide-angle	2–5 mm	Moderate (risk of warping)	Moderate, absorbs some blue	~\$4–\$6	Internal light smoothing (test only)
Frosted PMMA Sheet (2 mm)	~85%	Moderate uniformity	2 mm	Good (low warping)	Minimal color bias	~\$3–\$5	Internal grow light diffuser
Polycarbonate Sheet	~75–80%	Moderate	1–3 mm	High (impact/heat resistant)	Some spectral shift possible	~\$4–\$7	Internal under-LED applications
Matte Diffuser Film	~70–85%	Highly variable	<0.5 mm	Poor (heat degradation risk)	Depends on coating thickness	~\$2–\$4	Low-heat zones or short-term use

Figure 28: Table comparing various types of light diffusers for different parts of the system.

3.7.4 Spectrometers

The Bio-Sense Pot incorporates two spectrometer systems, each serving a distinct role in managing light quality and spectral distribution. The external spectrometer is tasked with monitoring the spectral composition of ambient light, providing the system with feedback on natural light composition throughout the day. This allows the system to intelligently adjust the grow light output to supplement missing spectral bands in terms of intensity or composition, or reduce unnecessary output when the ambient spectrum is already sufficient. The internal spectrometer, by contrast, is dedicated to monitoring the spectral output of the grow lights themselves. Because the LED modules do not provide built-in spectral reporting, this spectrometer ensures the plant receives the correct spectral balance, especially as dynamic lighting adjustments are made in response to sensor input.

Both systems share a common goal, maintaining spectral fidelity for optimized plant growth, but differ in implementation. The external spectrometer will rely on a commercially available, self-contained sensor with appropriate resolution and interface compatibility. The internal spectrometer will be a custom system using a fully discrete optical path, leveraging a custom lens, slit, and grating setup to analyze the emitted grow light with precision. This section explores the optical and practical requirements of both spectrometers, evaluates potential sensor and system configurations, and outlines the decisions guiding their final selection and implementation.

3.7.4.1 Design Requirements and Constraints

The dual spectrometer configuration in the Bio-Sense Pot is shaped both by functional objectives and the constraints of the system's form factor, cost, and optical layout. While the internal and external spectrometers both serve to characterize the spectral distribution of light, they operate in different environments and fulfill different roles, which in turn defines the constraints on their design and implementation.

The external spectrometer is intended to measure the spectral composition of ambient light, enabling the system to detect missing spectral bands or changes in color temperature throughout the day. This allows the grow light behavior to be adjusted not only in intensity but also in spectral composition, helping ensure the plant receives a balanced light profile. The spectrometer must be sensitive in the 400–700 nm range (photosynthetically active radiation) with sufficient resolution to distinguish between major bands (e.g., red, blue, green) relevant to plant development. It must also integrate cleanly into the existing electrical system, communicating over I²C or SPI and operating within a 3.3V–5V logic range. Since the external spectrometer is passively exposed to uncontrolled outdoor or indoor light, it must also be mechanically stable, shielded from contamination, and mounted behind the 600 grit glass diffuser discussed earlier to help normalize directional input.

The internal spectrometer serves the function of measuring the spectrum of the Bio-Sense Pot's own grow light output. Because the LED modules in use do not natively report spectral content, the internal spectrometer provides the system with feedback on

the exact wavelengths being delivered to the plant. This data enables more accurate dynamic adjustments based on both internal and ambient feedback. The internal spectrometer is also custom-built, requiring a defined optical path consisting of a collection lens, slit, collimating lens, diffraction grating, focusing lens, and a linear sensor array. Key constraints include optical alignment, enclosure space, lens focal lengths, and maintaining high transmission within the PAR region. Additionally, the capture device must be high enough resolution to resolve individual LED bands and fast enough to respond to system-level spectral changes in real time.

Both systems must operate within the power and size limits of the Bio-Sense Pot enclosure and must avoid adding significant complexity to the system's wiring or feedback processing. Careful consideration is also required to ensure the two spectrometers do not introduce spectral overlap or misalignment in their respective feedback loops. While the external spectrometer must be durable and self-contained, the internal spectrometer must remain optically precise and configurable within a constrained physical footprint.

3.7.4.2 Types of Spectrometers

Several spectrometer configurations were evaluated for the Bio-Sense Pot, particularly concerning the internal system tasked with analyzing grow light output. While many commercial spectrometers exist, most are either cost-prohibitive, physically oversized, or incompatible with the system's embedded and space-constrained architecture. To enable full control over layout and integration, a discrete optical spectrometer architecture was selected. This approach allows for precise control over lens focal lengths, sensor position, and resolution—while maintaining a compact footprint suitable for internal mounting. Meanwhile the pre-bought external spectrometer only requires housing and a diffusion glass.

Grating-based spectrometers, the most common type for visible light applications, operate by dispersing incoming light through a slit and directing it through a diffraction grating, where it is spatially separated into constituent wavelengths. A focusing lens then projects this spectrum onto a linear sensor array. This layout offers high resolution, straightforward construction, and a wide degree of tunability based on component selection [27]. It was selected as the foundation for the internal spectrometer due to its simplicity and flexibility. The diffraction grating can be chosen for either higher dispersion or broader coverage, and the use of a linear CCD (such as the TSL1401) allows spectral data to be digitized for use in the system's feedback loop.

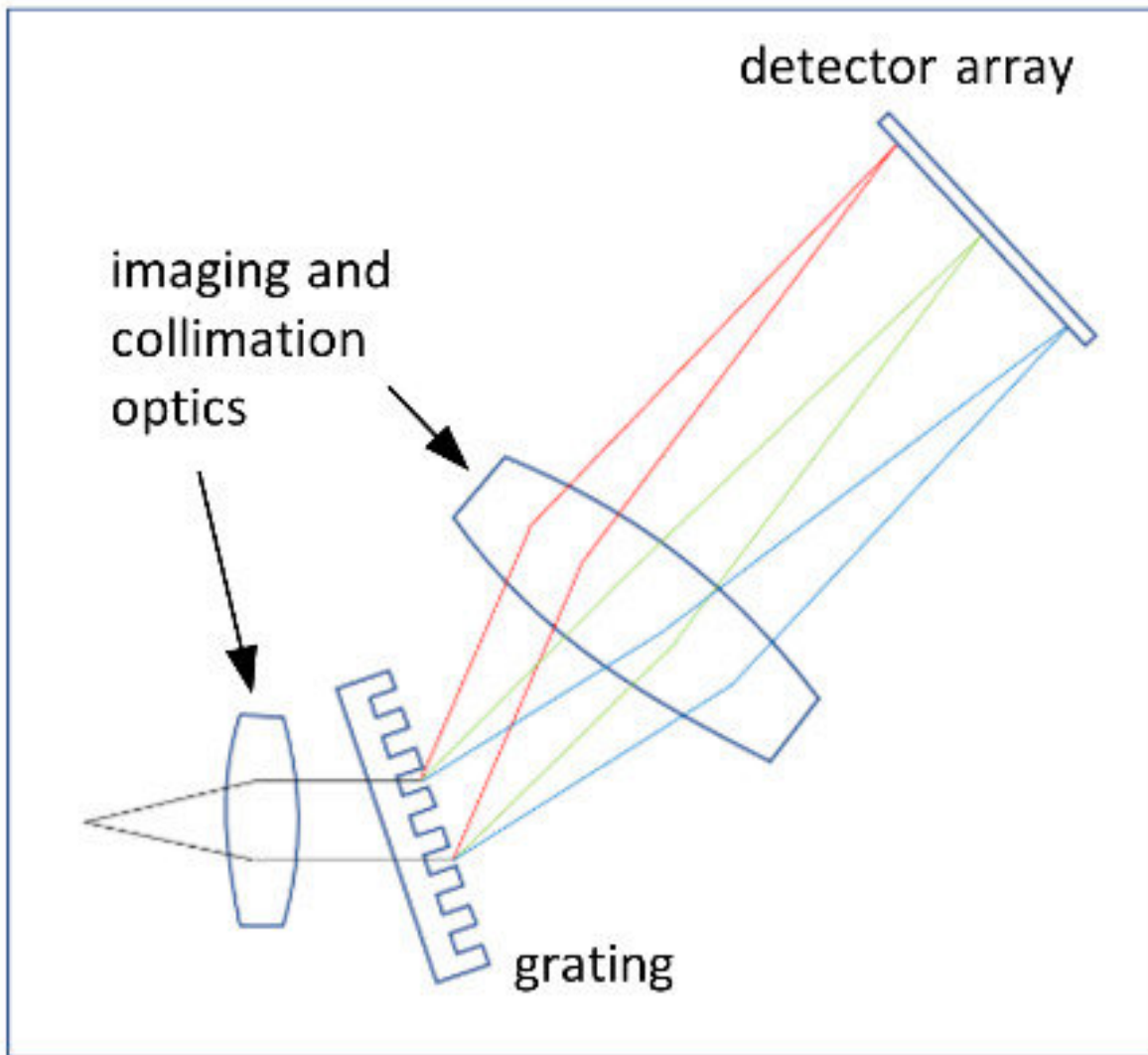


Figure 30: Schematic design of a transmission grating spectrometer system

Other spectrometer types were considered but ultimately ruled out. Prism-based spectrometers, which rely on refractive separation rather than diffraction, offer low chromatic aberration but typically require longer optical paths and are more difficult to shrink to our desired spectrometer size. Their curved dispersion makes them less suitable for compact builds, and alignment is more complex when trying to fit them within an embedded enclosure. Fourier-transform spectrometers, such as those used in IR or Raman systems, offer high resolution and wide dynamic range but are generally far too complex and expensive for the intended application. Similarly, interference-based filter arrays like Fabry–Pérot or MEMS tunable filters are attractive for compact systems but remain difficult to source at a low cost and often require custom calibration and software to decode their output.

Ultimately, the grating-based design was selected for its balance of compactness, cost-effectiveness, and sufficient spectral resolution for plant-centric applications. Its

modular nature allows individual components—slit width, lens focal length, sensor pitch—to be tuned as needed to align with the system’s internal geometry and expected spectral features.

Spectrometer Type	Wavelength Range	Resolution (approx.)	System Size	Interface Complexity	Cost Estimate	Suitable for Embedded Use?	Notes
Grating-Based (Discrete)	400–700 nm (configurable)	~5–15 nm (component-dependent)	Compact–Modular	Moderate (custom optics)	\$20–\$60	Yes	Selected for internal spectrometer
Prism-Based	400–700+ nm	~10–30 nm (nonlinear spread)	Long optical path	High (complex alignment)	\$50–\$150	No	Misalignment risk in small enclosures
Fourier-Transform (FTIR style)	400–IR (varies)	<1 nm (theoretical)	Large	Very High (calibration + moving parts)	\$300+	No	Overkill; better for NIR or lab use
Filter Array (Fabry–Pérot / MEMS)	400–1100 nm	~10–20 nm (channel-limited)	Very Compact	High (firmware + post-processing)	\$200+	Not ideal	Difficult to source affordably
Multi-Channel Sensor (e.g. AS7341)	350–1000 nm	Fixed 11-channel bands	Very Compact	Low (I ² C, onboard gain)	\$20–\$30	Yes	Selected for external spectrometer

Figure 31: Table comparing different types of spectrometers.

3.7.4.3 Component Evaluation and Selection

The external spectrometer is responsible for measuring the ambient light spectra in uncontrolled lighting environments. Unlike the internal spectrometer, which is built from discrete components, the external spectrometer will be a pre-assembled, off-the-shelf module selected for compatibility with the ESP32 and sufficient spectral resolution in the visible range.

Candidate devices include:

- AS7341 (Adafruit / AMS) – A compact, multi-channel spectral sensor with 11 discrete channels across the visible and near-IR range. Communicates via I²C and includes onboard gain and integration time control. Small form factor and low power make it ideal for embedded systems.
- SparkFun Triad Spectroscopy Sensor (AS7265x) – Higher resolution than the AS7341 with broader spectral coverage (UV to NIR), but physically larger and more complex to integrate.
- DFRobot Gravity Spectral Sensor – Lower-cost alternative with moderate spectral coverage and simple I²C integration.

The AS7341 has been identified as the most viable option due to its balance of spectral range, cost (~\$20–30), and proven compatibility with microcontroller-based systems. When paired with the previously selected external glass diffuser, and adequate housing, this sensor will likely provide stable, normalized readings of ambient light spectra. This allows the system to adjust the grow light output based on specific missing bands in sunlight or indoor lighting, improving spectral targeting without unnecessary power draw.

The internal spectrometer design is based on a compact, grating-based configuration using discrete optical components. This layout was selected for its tunability and ease of alignment within the system's constrained geometry. The optical path consists of a collection lens, a narrow slit, a collimating lens, a diffraction grating, a focusing lens, and a linear capture device. Each component has been chosen with consideration for size, cost, and the ability to resolve the dominant spectral bands emitted by the system's LED grow lights.

The current optical design targets a slit width of 100 to 200 μm , narrow enough to provide adequate resolution while still allowing enough light throughput for detection. The collimating and focusing lenses are expected to have focal lengths in the range of 25 mm to 50 mm, striking a balance between spectrometer system length and optical clarity. It should be noted that shorter focal lengths allow for more compact builds but may introduce aberrations that reduce spectral fidelity, this will be investigated.

The diffraction grating will likely be a 600 to 1000 lines/mm transmission grating, chosen based on the desired balance between resolution and spectral spread across the 400 to 700 nm range. Selection of the grating parameters, along with the final lens arrangement, will define the size of the projected spectrum and determine whether the full spectral range can be captured on the sensor.

The dispersed light will be projected onto a TSL1401 linear CCD array, a compact 128 pixel, monochrome, sensor that we have chosen as the final capture device due to its balance of simplicity, compatibility, and resolution. The TSL1401 was selected over higher-resolution or color-sensitive alternatives because it offers several key advantages for this system. Its linear form factor makes it ideally suited for capturing spectrally dispersed light across a single axis without requiring interpolation or pixel remapping. It is also readily compatible with the ESP32, using an analog output that can be digitized with minimal circuitry. Compared to full camera modules or image sensors, the TSL1401 reduces data overhead and simplifies system integration while still providing sufficient resolution to distinguish between the discrete spectral peaks emitted by RGB LED arrays. Additionally, the sensor is available, inexpensive, and backed by existing open-source libraries and various support pages, reducing development overhead and allowing for easier and faster testing and prototyping to be done. These traits make it a practical and reliable option for the internal spectrometer's capture stage, especially during the early design cycle.

Because of the number of interdependent optical parameters, final selection of the optical components—slit size, lens focal lengths, and grating density—will require testing in both lab conditions and Zemax simulations. These tests are essential to confirm that the chosen configuration fits within the system's spatial limits and achieves the desired resolution before funds are committed to components that may ultimately prove incompatible or ineffective. This approach reduces risk and ensures the internal spectrometer design remains both functional and cost-effective during the prototyping phase.

3.7.5 LCD Dome

The LCD dome is a potential component within the Bio-Sense Pot project, designed to provide dynamic light shielding over the plant area. Its intended function is to regulate exposure to intense ambient light by adjusting optical transmission in real time. In conditions where ambient light exceeds the upper threshold for photosynthetic efficiency, detected by the ambient light intensity sensor, the dome would enter an opaque or semi-opaque state, limiting excess exposure without requiring changes to the grow light behavior. This would serve as a secondary layer of regulation, improving the system's ability to maintain optimal lighting conditions and protect the plant from light oversaturation.

The core concept relies on the use of a switchable material—typically a liquid crystal (LC)-based film or polymer—that can modulate transparency when voltage is applied.

This would allow the dome to respond dynamically to feedback from the external light sensor, darkening only when needed and returning to transparency when ambient levels fall within acceptable bounds. In this way, the dome acts as a passive optical actuator, governed by the system's feedback logic but requiring no moving parts. However, practical implementation of this feature presents several challenges that may not be able to be solved given the project time-constraints. Most commercially available LC films are designed for flat-panel applications, such as privacy windows or projection screens, and are not intended to be shaped into hemispherical or dome-like structures. Flexible or curved implementations of LC films do exist, but they are primarily produced in bulk for industrial clients and are typically priced far beyond the budget of early-stage prototyping. Even sheet-based options that are flexible in one dimension tend to be expensive, hard to source in small quantities, or untested for long-term stability in a curved configuration. Given these limitations, the LCD dome is currently being treated as a stretch goal. While the concept remains feasible in principle, the cost, sourcing, and integration complexity place it outside the scope of the system's primary development cycle. Further exploration into alternative materials, simplified geometries, or partial implementations (such as flat shielding panels) may be conducted if time and budget allow during later development stages.

3.7.5.1 Design Requirements and Constraints

The design of the LCD dome is governed by a unique set of requirements distinct from other optical components in the Bio-Sense Pot. As a dynamically controlled light-shielding structure, it must maintain high optical clarity and transmission in its default transparent state, while providing just as effective light attenuation when activated. The transition between these states must be smooth and reversible, ideally with a fast response time and minimal visual artifacts. Because the dome serves as a shielding layer rather than a precision optical element, uniformity of diffusion is much less critical than consistent control over transmission.

A notable requirement is electrical compatibility with the system, particularly the ability to operate from a low-voltage DC supply that can be safely switched via the ESP32 microcontroller or a secondary driver module. The system must be able to toggle the opacity state in response to sensor feedback without introducing significant power draw or thermal load. The dome must also maintain consistent optical behavior under varying ambient lighting and temperature conditions, especially when deployed outdoors or near windows.

Mechanical requirements impose some of the most challenging constraints. The material must either be flexible enough to form a curved structure, or compatible with a segmented or faceted dome geometry. In either case, it must maintain structural integrity without delaminating, creasing, or distorting the liquid crystal layer. The overall form factor must fit around or above the plant area without interfering with the grow light array or upper sensor housing. Weight and thickness have to remain low to avoid introducing stress on the surrounding enclosure or requiring additional mechanical support components.

Finally, the cost and time inherent to the sourcing of materials represents the main limiting factor. To be viable within the scope of the current project, the dome material must be obtainable in small quantities and at a reasonable price point. Current research indicates that most curved or flexible LCD materials are priced for bulk industrial orders and are unlikely to be available at the scale or budget required for early-stage prototyping. I have tried contacting several companies in the hopes that I could order a small amount of their product, but I have yet to see a reply from any. These factors position the LCD dome as a stretch goal, with further investigation required to determine whether a practical implementation is feasible within the timeline of the Bio-Sense Pot's initial development cycle.

3.7.5.2 Types of LCD and Switchable Materials

Several categories of LCD and variable opacity materials have been identified as possible candidates for the LCD dome material, though each requires further research and validation. Most options originate from adjacent applications such as privacy panels often found in office buildings, automotive glass, or consumer displays, and may not be optimized for the scale, curvature, or cost requirements of the Bio-Sense Pot. However, a few classes of materials show potential for adaptation if sourcing or modification proves feasible.

Polymer Dispersed Liquid Crystal (PDLC) Films are among the most common switchable materials used in privacy glass applications. These films offer good on/off contrast, fast switching speeds, and moderate voltage requirements (typically 24–48V AC). In their transparent state, the LC molecules align to allow light through; in the off state, they scatter light and become opaque. PDLC films are appealing due to their relatively low power consumption and widespread availability in flat-sheet form. However, they are primarily designed for flat glass panels, and flexible or curved versions tend to be expensive or only available through high-volume industrial orders.

Suspended Particle Devices (SPD) offer an alternative electro-optic approach, using micro-particles suspended in a liquid that align when voltage is applied. While SPDs offer deeper light blocking and better clarity when active, they are less commonly available in the hobby or research market and typically require proprietary driving circuits. Cost and availability remain limiting factors, though their performance is appealing for dynamic shading applications.

Electrochromic materials, found in smart windows and mirrors, can change their opacity through redox reactions. These materials require very little power to maintain their state but often suffer from slower switching speeds and limited lifespan under repeated cycling. Their compatibility with curved surfaces and custom enclosures is limited, and the cost of small-quantity sourcing can be prohibitive for early-stage development.

In the broader consumer and maker space, some low-cost flexible LCD panels used in educational kits or toy displays may provide a pathway toward partial or simplified implementation. While these are not designed for light control or transparency switching, their underlying technology and driver compatibility make them worth

exploring in the context of future adaptations or flat-panel substitutes, if only as a proof of concept that this idea could work if taken further along a longer timeline with more money to spend.

Overall, while several technologies show promise in terms of optical performance or electrical compatibility, none have yet met the combined criteria of curvature, cost, and sourcing accessibility. As a result, the LCD dome remains in the conceptual phase, with additional research required to determine whether a functional prototype can be created within the system's constraints.

3.8 Software

For the development of our automatic watering system, selecting the appropriate software for schematic capture and PCB (Printed Circuit Board) design is crucial. Several software tools are available in the industry, each with distinct features, advantages, and limitations. The primary tools we considered include EasyEDA, Multisim, LTSpice, and Eagle Fusion 360. These tools will assist in designing, simulating, and prototyping the electronic circuit, ensuring optimal performance and efficiency in our project.

3.8.1 EasyEDA

EasyEDA is a cloud-based schematic and PCB design tool that provides an integrated workflow, from circuit design to PCB layout and simulation. It is a user-friendly platform, making it ideal for students and professionals looking for an accessible solution. One of its key advantages is the availability of a free tier with essential features, as well as its cloud-based nature, allowing users to access designs from any device. Additionally, EasyEDA provides a large component library and integrates with LCSC for seamless component sourcing. However, its simulation capabilities are relatively limited compared to more advanced tools. The free version also requires public project sharing, which may not be suitable for proprietary designs. While EasyEDA offers a simple interface for beginners, some advanced features require a paid subscription.

3.8.2 MultiSim

Multisim, developed by National Instruments, is a widely used software for circuit simulation and PCB layout. It is particularly strong in SPICE-based simulations, making it suitable for analyzing circuit behavior before physical prototyping. The software features a powerful SPICE simulation engine with real-time analysis, an extensive library of pre-built components, and strong integration with LabVIEW for hardware interfacing. It is frequently used in both academic and industrial settings for circuit education and prototyping. However, Multisim is a subscription-based tool, making it expensive for small-scale projects. It also requires installation, as it is not cloud-based,

and while it does support PCB layout, its capabilities in this area are not as advanced as dedicated PCB design tools.

3.8.3 LTSpice

LTSpice, developed by Analog Devices, is a free SPICE simulation tool focused on analog circuit design and power electronics analysis. It is particularly optimized for simulating analog circuits and power supplies, offering fast simulation speeds with detailed waveform analysis. A major benefit of LTSpice is that it is completely free to use with no licensing restrictions. However, it lacks PCB design capabilities and is strictly for circuit simulation. Additionally, its component library is more limited compared to other tools, and it has a steeper learning curve for beginners.

3.8.4 Eagle Fusion 360

Eagle Fusion 360 integrated into Autodesk Fusion 360, is a professional-grade PCB design tool known for its extensive features and reliability in creating complex circuit layouts. It is widely used in the industry due to its advanced routing, design rule checking, and large component library with third-party integrations. Eagle has strong community support and extensive documentation, making it a preferred tool for professionals. However, it operates on a subscription-based model, which may be a drawback for budget-conscious users. Compared to EasyEDA, it has a steeper learning curve and requires installation rather than being cloud-based. While it does not include circuit simulation like Multisim or LTSpice, its PCB design capabilities are among the best available.

3.8.5 Software Comparison and Selection

Given the requirements of our project, we need software that supports both schematic design and PCB layout, while also providing simulation capabilities for circuit validation. The comparison is summarized below:

Software	Cost	Cloud Based	Schema tic Capture	PCB layout	Simulatio n	Best for
EasyEDA	Free/Paid	Yes	Yes	Yes	Limited	Beginner and rapid prototyping
Multisim	Paid	No	Yes	Limited	Advanced	Academic and industry simulation
LTSpice	Free	No	Yes	No	Excellent	Analog and

						power electronics analysis
Eagle Fusion 360	Free/Paid	No	Yes	Yes	No	Professional PCB design

For our smart plant pot project, EasyEDA appears to be the most suitable choice due to its cost-effectiveness, cloud-based access, and integration with PCB manufacturing services. While LTSpice can be used for analog circuit verification, EasyEDA will be the primary tool for schematic capture and PCB design, ensuring an efficient and streamlined development process.

3.9 Microcontroller Selections

3.9.1 Introduction

The selection of the microcontroller is going to be extremely important as it is going to be the brain of the project and is required to be able to receive and send information while at the same time using that data to help create the best environment possible for the plant.

The smart plant pot will have the ability to sense moisture in the soil, sense temperature and temperature changes, and detect light intensity. Knowing this our microcontroller needs to be able to receive information from multiple sources at the same time, meaning they need to be able to handle multitasking. The microcontroller also needs to be able to control the components that are being used to do the work of controlling the environment, including the water pump and growth lamp. Finally, the board needs to be able to send data over WiFi, this is extremely important as the application is going to be a very big component when it comes to interacting with the smart pot so it needs to be equipped to do so.

3.9.2 Microcontrollers

When looking at the options of the microcontrollers that were available we noticed that there were 3 main types that kept coming up, the Arduino series, the ESP series, and the Raspberry Pi series (this includes all variations of these boards as well). The Arduino is a very popular board that has a large community. It is often used for homemade electronics projects and is the most beginner-friendly out of the 3 options. There are many different variations of the board like the Uno (basic board), Nano (compact version of Uno), and Mega (larger and more powerful version of Uno), but the best board for this project would be the Arduino MKR Series, specifically the MKR WiFi 1010. The MKR WiFi 1010 contains the input and output capabilities that we need as it can easily interface with sensors and motors using analog and digital pins, and the board also contains sufficient processing power for handling real-time data from multiple

sensors. Unlike the other boards and as the name states, the MKR WiFi 1010 comes with a WiFi module that satisfies the condition of having the capacity to connect to the internet and using different protocols to send information. The advantages of this board are the fact that it is very beginner-friendly and that it is much more powerful than the other Arduino boards so it can handle more sensors. For firmware development, the Arduino ecosystem provides the Arduino IDE, a simple and widely used development environment that supports the C/C++ programming language. The IDE includes built-in libraries for handling networking, sensor integration, and communication protocols, making it easy to get started and deploy code.[64]

The ESP boards are developed by Espressif Systems and like the Arduino, they offer multiple boards as well, their most popular being the ESP8266 and the ESP32. The best board for this project would be the ESP32 as the ESP8266 is a WiFi-only board and is often used for smaller projects because it uses a single-core processor. The ESP32 is a board that offers both WiFi and Bluetooth, currently, the project has no intentions of using Bluetooth for connectivity but it is still good because it is providing more options for communication and future-proofing the device. The board has enough general-purpose input/output pins to handle multiple sensors simultaneously. Similar to the MKR WiFi 1010, the ESP32 supports I2C and SPI communication protocols, which are useful for integrating various sensors and actuators. The ESP32 also is good for low power consumption as it supports low-power modes, which is crucial for IoT devices to maximize battery life when the system is operating on a limited power supply. One of the biggest advantages is that the ESP32 is a dual-core board, meaning not only is it much more powerful, but that also means that the board supports true multitasking and can run multiple tasks in parallel. For firmware development, the ESP32 uses the ESP-IDF (Espressif IoT Development Framework), which provides control over the hardware and allows for efficient, low-level programming. But, it is also compatible with the Arduino IDE and MicroPython, making development accessible for both beginners and advanced users. The ESP-IDF is preferred for projects requiring optimization, whereas Arduino IDE makes prototyping easier.[65]

The Raspberry Pi is a single-board computer developed by the Raspberry Pi Foundation and is used for many projects from creating simple electronics to complex industrial applications. There are multiple iterations of this board but the most common and up-to-date board is the Raspberry Pi 4. Unlike the Arduino and the ESP32 the Raspberry Pi 4 is a real computer and thus it comes with a quad-core ARM Cortex-A72 CPU running at 1.5 GHz, 8 GB of RAM, both ethernet and Wi-Fi, several USB ports, and an HDMI port that can be used for connecting to additional displays. This shows that the Raspberry Pi is much more powerful than the previously mentioned boards. This means that if wanted, the Raspberry Pi could not only take in data from the sensors but also it could do all the processing of the data on the board without the need to send it to an external device. The Raspberry Pi also comes with a Linux-based operating system giving us access to a wide variety of tools that would otherwise be unavailable on other boards and because the board runs its own OS we could actually host everything on the Raspberry Pi meaning the server, database, APIs, and code files to go along with the sensors of the pot. The firmware development for the Raspberry Pi is different from the other boards because it runs a full operating system. This allows us

to use various programming languages such as Python, C++, and JavaScript. The most common development environments include the Thonny IDE for Python, Visual Studio Code, and SSH-based remote development using the command line. This flexibility makes the Raspberry Pi more suitable for complex applications where an operating system and multitasking are necessary.[66]

The ESP32 is the best choice for this project because it offers the right balance of power, connectivity, and efficiency. While the Raspberry Pi 4 is more powerful, it requires an OS and higher power consumption, making it unnecessary for a sensor-based IoT device. The Arduino MKR WiFi 1010 is beginner-friendly but lacks the processing power and multitasking capabilities needed for handling multiple sensors efficiently. The ESP32 stands out with its dual-core processor, built-in WiFi and Bluetooth, and support for various communication protocols, all while maintaining low power consumption. Its flexibility in programming environments like ESP-IDF, Arduino IDE, and MicroPython also makes development more adaptable. With strong community support and robust features, the ESP32 is the most efficient and scalable option for this smart plant system.

Feature	Arduino MKR WiFi 1010	ESP32	Raspberry Pi 4
Manufacturer	Arduino	Espressif	Raspberry Pi Foundation
Processor	SAMD21 Cortex-M0+ (32-bit, 48 MHz)	Dual-core Xtensa LX6 (240 MHz)	Quad-core ARM Cortex-A72 (1.5 GHz)
Memory (RAM)	32 KB SRAM	520 KB SRAM, 8 MB PSRAM (optional)	Up to 8 GB LPDDR4
Storage	256 KB Flash	Varies (Flash storage, external possible)	microSD card (supports large capacities)
Wireless Connectivity	WiFi, Bluetooth Low Energy (BLE)	WiFi, Bluetooth	WiFi, Ethernet
GPIO Pins	22 digital, 7 analog	34 GPIO	40 GPIO
I/O Interfaces	I2C, SPI, UART, PWM, ADC, DAC	I2C, SPI, UART, PWM, ADC, DAC,	I2C, SPI, UART, USB, HDMI, Audio Output

		Touch Sensors	
Power Consumption	3.3V ~10–20 mA	3.3V ~20–50 mA (supports deep sleep)	5V ~600–700 mA
Multitasking	No (Single-threaded)	Yes (Dual-core, FreeRTOS-based)	Yes (Runs full OS, supports multitasking)
Operating System	None (bare-metal programming)	None (bare-metal, FreeRTOS)	Raspberry Pi OS (Linux-based)
Development Environment	Arduino IDE (C/C++)	ESP-IDF, Arduino IDE, MicroPython	Raspberry Pi OS, Python, C++, VS Code

3.10 Wireless Communication & IoT Connectivity

3.10.1 Introduction

Wireless communication is one of the most important aspects of any IoT project because it allows devices to transmit and receive data without needing a physical connection. For this smart plant system, having a reliable wireless communication method is necessary because the system needs to remotely monitor sensor data and send it to an external device for processing or display. Whether it's checking moisture levels from a phone or automating responses based on environmental conditions, the system relies on a stable connection to function effectively. To determine the best option, this section will compare Wi-Fi and Bluetooth as potential wireless connection methods, evaluating their range, power consumption, and data transfer capabilities. Additionally, different communication protocols like MQTT, HTTP, and WebSockets will be analyzed to see which one is best suited for efficient and real-time data transfer.

3.10.2 Wireless Connection Methods

The two methods of wirelessly connecting our devices will be through Wi-Fi and Bluetooth. Wi-Fi allows devices to connect to the internet and from there, information can be sent and received from anywhere. Wi-Fi operates mainly on both the 2.4GHz(standard) and 5GHz(high speed) and offers the ability to transfer data at high speeds and at long distances. Wi-Fi is commonly used for devices that require constant connectivity, remote data access, and large data transfers. The board that we chose, the ESP32 has Wi-Fi capabilities which will enable us to transmit data wirelessly.[67]

Bluetooth is a short-range wireless communication method that is designed for connecting devices directly to one another. It operates on the 2.4GHz band and is optimized for low power consumption, this makes it a good choice for devices that will be running off of a limited power supply. The main downside of Bluetooth is its limited range which is normally around 10 meters making it impossible to transfer information unless you are close to the device, this means that if someone were to leave their home they wouldn't be able to see any updates for their plant.[68]

For this project, Wi-Fi is the best choice for connecting our board to the external device(cell phone), because using Wi-Fi we can directly connect to the cloud that will store everything needed for our application. Our external device will also be connected to the cloud allowing for real-time remote monitoring without requiring a nearby device to relay data. Wi-Fi also has the ability to transfer data at higher speeds, preventing delays in updates. Also, Wi-Fi has an almost infinite range allowing for connectivity at any location, and when addressing the future possibilities of this project its extended range makes it ideal for large-scale projects and it supports multiple devices simultaneously, making it a scalable solution for expanding the system in the future. While Bluetooth is more power-efficient, its short range, limited data throughput, and reliance on a nearby device make it less practical for a system that requires continuous monitoring, real-time updates, and cloud-based control.

Feature	Wi-Fi	Bluetooth
Range	Unlimited	~10m (indoor)
Dataspeed	Up to 600 Mbps (Wi-Fi 6)	1–3 Mbps (Classic), ~2 Mbps (BLE)
Connectivity	Connects directly to the cloud	Requires a nearby device (phone, hub) to send data online
Multi-Device Support	Supports many devices at once	Supports fewer simultaneous connections

3.10.3 Wireless Communication Protocol

The methods that are being considered for the wireless communication protocol are HTTP, MQTT, and WebSockets. The wireless communication protocol that is chosen is going to be what connects the ESP32 to the internet and allows us to both send and receive data. One widely used protocol is the Hypertext Transfer Protocol(HTTP) and it allows communication between clients and servers over the Internet. The client sends requests and the server processes those requests and sends a response back. HTTP is

also a stateless protocol, meaning that each request is independent and does not retain session data between transactions. This makes it simple to implement and is widely compatible with existing web technologies. HTTP works really well for sending sensor data to the cloud, but because of its request-response model, it is less efficient for receiving real-time commands since the ESP32 would have to constantly check for new instructions. This increases power consumption and network traffic, making it less ideal for applications that require quick real-time response times. This makes HTTP great for one-way communication but less efficient for bi-directional communication.[69][70]

MQTT stands for Message Queuing Telemetry Transport and is a lightweight, publish-subscribe messaging protocol designed for low-bandwidth, high-latency, or unreliable networks. Unlike HTTP which uses the request-response model, MQTT's publish-subscribe model uses a central central server called a broker and it has clients that subscribe to it. This way when a message is published from one client to the broker, the broker can redistribute that message to any or all of the clients that subscribe to it. And also unlike HTTP, MQTT is optimized for bi-directional communication so any client that is subscribed can also publish a message. One big advantage of MQTT is its low overhead and real-time communication, making it great for devices with limited resources, which is crucial for our smart plant system. It also supports three levels of Quality of Service (QoS), ensuring reliable message delivery and efficiency for low-power devices. However, MQTT does have some drawbacks, such as the complexity of setting up and managing a broker, the lack of automatic device discovery, and the broker acting as a potential single point of failure. Despite these disadvantages, MQTT is a great fit for our project due to its efficiency, real-time capabilities, and scalability.[71][72]

WebSockets is a communication protocol that provides full-duplex, bidirectional communication between a client and a server over a single, continuous connection. Unlike HTTP, which relies on a request-response model, WebSockets allow data to flow freely in both directions without repeatedly establishing new connections. This makes them ideal for real-time applications where low latency is important. In the smart plant system, WebSockets could be used to send sensor data to the cloud instantly and provide immediate updates to the user interface. If a user sends a command, like adjusting the watering schedule, the system would respond without delay. The setup involves a WebSocket server on the cloud and a client on the ESP32, with an initial HTTP handshake to establish the connection. While this approach is efficient for real-time communication, it may consume more power and resources compared to other protocols, especially on low-power devices. Security is also a key factor since persistent connections need proper encryption and authentication.[73][74]

After comparing HTTP, MQTT, and WebSockets, WebSockets stands out as the best choice for the smart plant system. HTTP, while simple and widely supported, relies on a request-response model that wouldn't be efficient for real-time monitoring. It would require constant polling to get updates, leading to unnecessary bandwidth use and slower response times. MQTT offers a lightweight, publish-subscribe model that's great for devices with limited resources, but it's mainly designed for scenarios with many devices or unreliable networks. Since the smart plant system will have a stable Wi-Fi

connection and only a few devices, MQTT's advantages wouldn't be as beneficial. On the other hand, WebSockets provide a persistent, bidirectional connection that allows real-time communication between the ESP32 and the cloud. This ensures sensor data can be sent and displayed instantly, and any commands from the user interface can be executed without delay. With its low latency and efficient use of resources, WebSockets is the most practical and effective choice for keeping the system responsive and user-friendly.

Feature	HTTP	MQTT	WebSockets
Communication Model	Request-response	Publish-subscribe	Bidirectional, full-duplex
Connection Type	Stateless	Persistent (client-broker)	Persistent (client-server)
Latency	100–500 ms	20–100 ms	30–150 ms
Efficiency	Not efficient for real-time	Efficient for many devices	Efficient for real-time data transfer
Scalability	Can be slow with many devices	Scalable in IoT setups	Ideal for systems with fewer devices
Use Case	General web communication	IoT devices with limited bandwidth	Real-time updates and interactive apps
Reliability	Reliable, but no session state	Reliable, but depends on broker	Very reliable, maintains connection
Bi-directional Communication	No	Yes	Yes

3.11 Cloud and Database Selections

3.11.1 Introduction

When it comes to storing and managing plant data, selecting the right database and storage solution is critical for ensuring reliable performance and seamless data access. The decision between SQL and NoSQL databases is an important one, as it will determine how data is structured, queried, and maintained. Additionally, choosing between cloud storage and local storage will impact the app's scalability, latency, and security. Each option has its own strengths and trade-offs, and understanding how these solutions fit into the overall system design will help in making the best choice for the project.

3.11.2 Cloud vs Local Storage

When it comes to storing the plant data collected from sensors, the main choices are local storage and cloud storage. Selecting the right storage method is essential for ensuring reliable access to the data and supporting remote monitoring capabilities. Local storage would involve saving the data directly on the ESP32 or the phone connected to the app. While the ESP32 has limited storage capacity, it could temporarily store sensor data before sending it to the phone for display. The app could also store data locally, allowing users to view recent plant information without needing an internet connection. However, relying solely on local storage could limit scalability and make remote access impossible, especially if users want to monitor plant health when they're not at home.[75][76]

Cloud storage offers a more flexible and scalable solution for storing plant data by using remote servers accessible over the internet. Instead of relying on the ESP32 or phone for data storage, information from the sensors would be sent to a cloud service where it can be securely stored and accessed from anywhere. Some popular options for cloud storage include AWS DynamoDB, Google Firebase, and Azure Cosmos DB, all of which provide real-time data synchronization and easy integration with mobile apps. For this project, using a cloud storage service would allow the app to retrieve and display the latest sensor readings, while also providing historical data for tracking plant health over time. Since the data is stored in the cloud, it remains accessible even if the phone is offline or the ESP32 disconnects. Cloud storage also enhances security by offering data encryption and authentication measures to protect sensitive information.[75][77][78]

Feature	Local Storage	Cloud Storage
Storage Location	On the ESP32 or phone	Remote servers managed by cloud providers
Accessibility	Limited to the local device	Accessible from anywhere

		with an internet connection
Latency	~0.1–10 ms	~100–1500 ms
Scalability	Limited by device storage capacity	Easily scalable with virtually unlimited storage
Reliability	Data loss risk if the device fails	Data backed up and replicated across servers
Security	Depends on device security	Enhanced security with encryption and authentication
Cost	Free after hardware purchase	May incur ongoing costs based on storage and bandwidth
Data Sharing	Difficult to share data across devices	Seamless data sharing and synchronization
Maintenance	User-managed backups and storage management	Managed by cloud provider with automated backups

3.11.3 Databases

For the storage of plant data in our smart plant system, we need to choose between SQL and NoSQL databases, as each offers their own advantages based on the kind of the data and scalability requirements. SQL databases, such as MySQL, are ideal for structured data that adheres to a fixed schema, making them good for projects where data relationships are important and complex queries are necessary. These databases store data in tables with predefined columns and rows, ensuring that the data is organized in a structured format. This makes it easier to maintain data integrity through features like ACID (Atomicity, Consistency, Isolation, Durability) properties. In our project, we would use a SQL database to store plant sensor data, where each sensor's readings can be stored in tables, and relationships between different types of data, such as plant types, sensor readings, and timestamps, can be easily managed using SQL queries. This would allow us to perform tasks like querying specific sensor data for analysis or generating reports on plant health over time, all while ensuring that the database remains consistent and reliable.[79][80][81]

NoSQL databases, like Firebase and AWS DynamoDB, offer an alternative to SQL databases by providing a flexible, scalable solution for handling large amounts of unstructured or semi-structured data. Unlike SQL databases, NoSQL databases do not rely on a fixed schema, which makes them suitable for constantly changing data and less rigid data relationships. This flexibility allows for easier horizontal scaling, as NoSQL databases can handle large volumes of data across distributed systems. In our

project, we would use a NoSQL database to store plant data because it can easily accommodate diverse types of sensor data without needing a predefined structure. For example, plant sensor readings might include various data types such as temperature, humidity, and soil moisture, each requiring different data formats. Using Firebase or AWS DynamoDB, we can store this data in a document-based or key-value format, where each sensor's data can be dynamically added or updated without disrupting the overall system. Additionally, NoSQL databases typically offer better performance for read and write operations at scale, making them a strong option for real-time data processing in IoT systems like our smart plant project.[79][80][81]

SQL and NoSQL databases are both good options for storing data in this project, each with its own strengths. SQL databases, with their structured schema and support for complex queries, are ideal for scenarios that require clear relationships between data points. They provide reliable data integrity and are well-suited for applications where consistency is critical. On the other hand, NoSQL databases offer flexibility and scalability, making them a strong choice for projects with large volumes of unstructured or semi-structured data. Since this smart plant system will involve frequent data updates from sensors and require efficient real-time access for the mobile app, a NoSQL database is the most practical choice. Specifically, Firebase Realtime Database stands out as the best option. It provides low-latency data synchronization, ensuring the mobile app receives real-time updates. Additionally, Firebase's seamless integration with other cloud services, simple setup, and scalable infrastructure make it a convenient and reliable choice. Ultimately, Firebase Realtime Database aligns best with the project's needs for real-time data access, scalability, and ease of use.[82]

Feature	SQL Databases	NoSQL Databases
Data Structure	Structured, relational tables	Flexible, document, key-value, or graph models
Schema	Fixed schema, requires a predefined structure	Dynamic schema, adaptable to changing data
Scalability	Vertical scaling (adding resources to a single server)	Horizontal scaling (adding more servers easily)
Data Integrity	Strong ACID compliance (Atomicity, Consistency, Isolation, Durability)	Eventual consistency, with optional strong consistency
Querying	Complex SQL queries with JOINS	Simple queries using document-based retrieval
Speed and	Efficient for structured data	Faster for large volumes of

Performance	and complex queries	unstructured data
Real-Time Data	Limited real-time capabilities	Excellent real-time data synchronization
Maintenance	Requires more management and optimization	Easier to maintain with automatic scaling and updates

3.12 Mobile and Web Development Selections

3.12.1 Introduction

Developing an intuitive and responsive interface for displaying plant data is a key aspect of this project. The choice of development framework will determine how efficiently the app is built and how well it performs across different platforms. Native frameworks like Swift and Kotlin provide optimized performance and seamless access to device features, while cross-platform solutions like Flutter and React Native offer quicker development with a single codebase. Another option is creating a web app, which can be accessed on any device with a browser, simplifying updates and reducing platform-specific challenges. Evaluating these options will ensure the best choice for delivering a user-friendly experience.

3.12.2 Frameworks

When looking at the development of the mobile app, the main framework choices to consider are native frameworks, like Swift for iOS and Kotlin for Android, cross-platform frameworks such as Flutter or React Native, and the option of creating a web app. The decision on which framework to use is crucial because it will affect the app's performance, development time, and how easily it can be maintained. Native frameworks, such as Swift for iOS and Kotlin for Android, provide the most optimized performance since they are tailored specifically for each platform. They allow direct access to platform-specific features like push notifications, GPS, and device sensors, making them ideal for projects that require intensive use of these features. While they require separate codebases for iOS and Android, native frameworks would ensure that the plant monitoring app is highly responsive and fully integrates with device capabilities, offering a smooth and reliable user experience. However, the major disadvantage of native frameworks is that they require maintaining two separate codebases, which can increase development time and complexity. This also means double the effort for bug fixes and feature updates, making it more challenging to keep the app in sync across both platforms.[83][84]

Cross-platform frameworks like Flutter and React Native are popular alternatives to native frameworks for mobile app development. These frameworks allow developers to write a single codebase that can be deployed to both iOS and Android, which significantly reduces development time and effort. With cross-platform frameworks, the plant monitoring app can be developed faster since there is no need to maintain

separate codebases for each platform. Additionally, these frameworks offer near-native performance and the ability to access device features like GPS and push notifications, though with some limitations compared to native development. The primary advantage of using cross-platform frameworks is the ability to support both iOS and Android simultaneously, which streamlines updates and maintenance. However, a notable disadvantage is that, while cross-platform frameworks have made significant strides in performance and functionality, they may still face limitations in handling complex platform-specific tasks or high-performance features. There may also be occasional compatibility issues when dealing with platform updates, as cross-platform frameworks may take time to fully support new platform features or changes. But, for a plant monitoring app, cross-platform frameworks like Flutter or React Native can offer a great balance between development efficiency and performance.[84][85][86]

Creating a web app for the plant monitoring system is another viable option to consider. Web apps are accessed through a browser, meaning they can be used on any device with an internet connection, eliminating the need for platform-specific development like native frameworks or cross-platform solutions. This makes the development process simpler, as there's no need to maintain separate codebases for iOS and Android. Additionally, web apps can be accessed on a wider range of devices, including desktops and tablets, providing flexibility for users to check plant health from multiple platforms. However, the downside to web apps is that they require a constant internet connection to function properly and might not be able to fully integrate with device-specific features like push notifications or GPS, depending on the browser's capabilities. For a plant monitoring system, a web app could work well if the primary focus is providing users with a dashboard and historical data, with real-time updates via browser-based communication like WebSockets or HTTP. [87][88]

When considering the best development option for the plant monitoring system, native frameworks, cross-platform frameworks, and web apps all have their strengths. Native frameworks like Swift and Kotlin offer the highest performance and seamless integration with device-specific features, but they require separate codebases, increasing development time and effort. Cross-platform frameworks like Flutter and React Native simplify the process by using a single codebase for both iOS and Android, making development faster while still providing good performance. However, for this project, creating a web app stands out as the best choice. A web app ensures accessibility from any device with a browser, allowing users to monitor plant data from their phones, tablets, or computers without needing to download an app. It also simplifies maintenance and updates since changes only need to be deployed once. While web apps may lack some native features, the primary focus of this project is on data visualization, notifications, and remote monitoring — all of which can be effectively handled through a responsive web dashboard. This approach will keep development efficient while providing a seamless user experience.

Criteria	Native	Cross-Platform	Web App
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	(Swift/Kotlin)	(Flutter/React Native)	
Performance	optimized for platform	Good, near-native performance	Moderate, depends on browser performance
Code Base	Requires separate codebases	Single codebase for both platforms	Single codebase accessible from any device
Maintenance	High, separate updates for each platform	Easier, single update across platforms	Easiest, updates deployed directly to the server
Device Integration	Full access to native features (GPS, sensors)	Limited access, but supports most common features	Limited access, relies on web APIs
User Accessibility	Requires app installation	Requires app installation	Accessible from any device with a browser
Offline Support	Strong, can leverage local storage easily	Moderate, with some offline capabilities	Limited, depends on browser caching

3.13 AI Integration

3.13.1 Introduction

AI integration is a key component of this project, enhancing the plant monitoring system with advanced features such as plant identification and an AI-powered assistant chatbot. These technologies will allow users to interact with the app more intuitively and dynamically, offering real-time responses and personalized guidance. By integrating AI, we can automate tasks like identifying plant species from images and providing users with valuable information about their plants, improving the overall experience. The decision on which AI approach to use is crucial, as it impacts the system's accuracy, user interaction, and scalability. In this section, we will explore different AI solutions and discuss the most suitable options for our project.

3.13.2 Plant Identification

For the plant identification system in this project, AI integration will be essential for accurately recognizing plant species from uploaded photos. Choosing the right AI

approach is important for ensuring reliable performance and a seamless user experience, one of the most practical options is using pre-trained API services. Pre-trained API services, such as Google Cloud Vision, Microsoft Azure's Computer Vision API, Plant.id API, and Clarifai, offer a convenient and powerful option for integrating plant identification into the project. These services are already trained on vast datasets, which means they can quickly and accurately identify a wide range of objects, including plants, from images. Using a pre-trained API would save significant development time, as the complex process of training a custom machine-learning model is avoided. For our plant identification system, these services could be used to process uploaded plant photos and return the species name, and other relevant details with minimal setup. The main advantage of this approach is the ease of integration and reliability, as these APIs are continuously updated and optimized by their providers. [89][90][91][92]

Custom machine learning models provide a more tailored approach to plant identification, allowing us to train a model specifically for the plant species relevant to the project. By using frameworks like TensorFlow or PyTorch, we can train the model on a custom dataset of plant images to improve its accuracy in identifying specific plants. This approach would give us more control over the training process and allow for adjustments to be made based on the needs of our system. The advantage of custom models is that they can be fine-tuned to recognize niche or rare plants that pre-trained APIs might struggle with. However, creating a custom machine learning model requires a significant amount of time and resources, both for dataset collection and training the model. Also, ongoing maintenance would be required to ensure the model's performance remains high. This option would be best suited for the project if there were a need for high accuracy with a specialized dataset or if the plant species being monitored are unique and not well-represented by existing APIs. [93][94][95][96]

Transfer learning is a technique that allows us to leverage a pre-trained machine learning model and adapt it to our specific task, such as plant identification, by fine-tuning it with a smaller dataset. This method builds upon existing models trained on large, diverse datasets, such as those used for image recognition, and adapts them to identify plant species by providing additional data relevant to our project. The advantage of transfer learning is that it significantly reduces the time and computational resources required for training, as the model already understands general patterns and features. By simply fine-tuning the model, we can improve its accuracy for plant identification without the need for a large dataset. This approach is efficient and cost-effective, especially for projects with limited data or resources. However, it may not offer the same level of customization as developing a fully custom model. Transfer learning strikes a balance between utilizing the power of pre-trained models and adapting them to the unique needs of our plant identification system. [97][98][99]

Edge AI solutions involve processing machine learning models directly on the device, such as on the ESP32 or a mobile phone, instead of relying on cloud-based services. This approach brings the power of AI to the "edge" of the network, closer to where the data is generated, which can greatly improve response times and reduce latency. For our plant identification system, Edge AI would allow the app or device to process plant

images locally, making the system faster and more efficient. This method reduces the need for constant internet connectivity and can be especially useful in situations where network access is limited or unreliable. Edge AI solutions also enhance privacy, as data does not need to be sent to external servers for processing. However, the main challenge lies in the device's limited computational power, which can restrict the complexity of the models used. To address this, we may need to either develop a custom AI model or fine-tune a pre-trained model for plant identification tasks. Fine-tuning a model (using techniques like transfer learning) could make it small enough and efficient enough to run on edge devices while still delivering high-quality results. Despite these challenges, for our project, Edge AI could offer a great solution by enabling real-time, efficient plant identification without relying on constant cloud access.[100][101][102][103]

Looking at the four AI options: Pre-trained API Services, Custom Machine Learning Models, Transfer Learning, and Edge AI Solutions, each offers its advantages and challenges. Pre-trained API Services provide a fast, reliable, and scalable solution, as they come with pre-built models that are already trained on vast datasets, making them well-suited for tasks like plant identification. The ease of integration is another key advantage, allowing for quick development and minimal setup time. While Custom Machine Learning Models and Transfer Learning offer more control over the AI's behavior, they come with the additional workload of training and fine-tuning models, which can be time-consuming and resource-intensive. Edge AI Solutions, though efficient in reducing latency and improving privacy, require powerful devices and can struggle with more complex models. Additionally, for our project, speed is not a critical factor, as this feature is expected to be used only occasionally by the user. Given the need for quick development, reliable results, and ease of integration, Pre-trained API Services will be the best choice. They strike the ideal balance between accuracy, efficiency, and integration simplicity, allowing us to focus on delivering a functional and user-friendly app without the added complexity of custom AI model development.

AI Option	Description	Advantages	Disadvantages	Use Case for Project
Pre-trained API Services	APIs that provide access to pre-built models for tasks like image recognition (e.g., Google Vision, AWS Rekognition).	Easy to integrate, high accuracy, minimal training needed, scalable.	May have usage limits, data privacy concerns, dependent on internet connectivity.	Best for plant identification, as they provide a ready-to-use solution with easy integration.

Custom Machine Learning Models	Models built from scratch using labeled data to train an AI system. Can be designed for specific tasks or optimized for particular datasets.	Full control over model, customizability, and optimization for specific tasks.	Requires significant expertise, large datasets, and time to train the model.	Suitable for tailored plant identification systems, but requires extensive development.
Transfer Learning	Using a pre-trained model on a large dataset and fine-tuning it for a specific use case (e.g., adapting a model trained on general objects to plant images).	Faster training, less data needed, still retains high accuracy.	Requires some expertise to fine-tune, may still need substantial computational resources.	Ideal for plant identification where custom training is needed but time and resources are limited.
Edge AI Solutions	Processing machine learning models directly on the device (e.g., ESP32 or mobile) without relying on cloud-based services.	Low latency, reduced reliance on internet, enhances privacy.	Limited computational power, harder to develop and integrate, may not support complex models.	Not ideal for this project as the plant identification feature should only be used occasionally and speed is not critical.

3.13.2.1 Pre-trained API Services

We have several Pre-trained API choices to consider for the plant identification system in our project. These services can significantly streamline the process by offering pre-built models for plant recognition based on uploaded images, saving us time and resources on model development. The main options are Google Cloud Vision API, Plant.id API, IBM Watson Visual Recognition, and Microsoft Azure Custom Vision, each with its own set of advantages and trade-offs that we must consider for the project.

Google Cloud Vision API provides robust image recognition capabilities and is capable of identifying thousands of objects, including plants. It offers high accuracy and reliability, making it a solid choice for plant identification. The service integrates well with other Google Cloud services, which can be useful for scalability. However, it can become expensive depending on the volume of usage, and it requires an internet connection for processing, which might limit its utility in offline situations. Despite these limitations, Google Cloud Vision would work well in identifying plants and could be integrated seamlessly into the app.[89]

Plant.id API specializes in plant recognition and offers a large dataset of plant species. It is tailored specifically for plant identification and provides accurate results based on image input. This service includes a free tier, but it also has paid options for higher-volume users. While its focus on plant species makes it more specialized compared to general-purpose image recognition APIs, the downside is that it may not have the same broad range of features as something like Google Cloud Vision. Despite this, Plant.id is a strong contender for our project because of its focus on plant identification and its affordable pricing structure.[90]

IBM Watson Visual Recognition provides powerful image classification tools and offers the ability to customize models for specific use cases, such as plant identification. It's a great option for users who want to fine-tune their models based on their unique datasets. While it provides high accuracy and flexibility, it can be more complex to set up compared to other options. The service can also be more expensive, especially with large volumes of image data. However, its deep integration with IBM's AI ecosystem makes it an appealing choice for advanced users who require more control and customization over their plant identification system.[91]

Microsoft Azure Custom Vision allows users to train custom models for specific tasks, including plant identification. It offers a pre-trained model option, but users can also fine-tune the model by uploading their own datasets, making it a flexible and customizable solution. However, the need for additional training data may slow down the initial setup and increase costs. While this is a powerful tool for those needing precise control over their model, it might not be as straightforward as some other pre-trained services. Still, Azure's integration with other Microsoft services and its scalability makes it a good option for projects with specific customization needs.[92]

Plant.id API is the most suitable option for our plant identification system. It's specifically designed for plant recognition, offering a highly specialized dataset that aligns perfectly with the goals of our project. The accuracy it provides in identifying various plant species is one of its strongest points, and its affordable pricing makes it a cost-effective choice. While alternatives like Google Cloud Vision API offer more general capabilities, they aren't as specialized for plant identification and may not deliver the same level of precision. Moreover, Plant.id's focus on plants streamlines the integration process, minimizing the need for extensive customization. This makes it the best choice for our plant identification feature, offering the right balance of specialized performance and ease of integration.

API Service	Key Features	Advantages	Disadvantages	Best For
Plant.id API	Specialized plant identification, large plant database	High accuracy, tailored for plant identification, affordable	Limited to plant identification, may not be as flexible for other image recognition tasks	Projects focused specifically on plant identification
Google Cloud Vision API	General image recognition supports multiple categories	Highly versatile, robust image processing capabilities, large dataset	Less specialized for plants, might not be as accurate for plant ID	General image recognition and broader use cases
IBM Watson Visual Recognition	General image recognition with custom training support	Can train models with custom datasets, versatile	Expensive, less focused on plants, setup can be complex	Custom recognition or use cases beyond plants
Microsoft Azure Computer Vision	General image recognition, custom model support	Large scale, extensive features, supports multiple recognition types	General-purpose, not specialized for plant identification	Broad image recognition with customization options

3.13.3 AI Assistant

The AI assistant chatbot will rely on various AI options, with Pre-trained NLP Models being an excellent choice for enabling natural and conversational interactions with users. These models are crucial for allowing the chatbot to understand and respond to user questions about plants accurately and contextually. Pre-trained NLP models, such as OpenAI's GPT or Google's Dialogflow, have been trained on large, diverse datasets, giving them the ability to handle a broad spectrum of queries about plant care, maintenance, and troubleshooting. In our project, using a Pre-trained NLP model is ideal as it allows us to focus on fine-tuning the model for plant-specific content instead of building the foundational language capabilities. This approach not only speeds up the

development process but also ensures a high-quality, user-friendly experience.[104][105][106][107]

Custom chatbot development with machine learning offers the potential for a more tailored, plant-specific conversational experience. By training a model specifically on plant-related data, we can ensure the AI assistant has a deep understanding of the unique needs of plants and can provide highly relevant advice. This approach involves collecting a large dataset of plant-related questions and answers, which would be used to train the chatbot, allowing it to improve over time as it interacts with users. While custom development allows for greater flexibility and specificity compared to pre-trained models, it requires significant effort in terms of data gathering, model training, and continuous refinement. For our project, this could be a good option if we want to create a highly specialized chatbot that delivers exceptionally accurate plant care advice, but it would require more resources and time compared to using pre-trained models.

Voice-activated AI assistants provide an interactive, hands-free way for users to engage with the plant care system. These assistants, powered by technologies like Google Assistant or Amazon Alexa, allow users to ask questions about their plants and receive responses through voice, making the experience more seamless and convenient. Integrating voice recognition capabilities into the plant monitoring system can enhance user engagement, especially for those who prefer speaking over typing. While these systems often rely on pre-trained models, integrating them into our project would allow for easy, natural interaction with the plant assistant. However, the challenge lies in ensuring that the AI can accurately understand and respond to plant-specific queries in a conversational manner. This approach might be ideal for users looking for an intuitive, voice-based experience, but it would require substantial integration efforts with existing voice platforms and might not offer the same level of plant-specific expertise as a custom chatbot or pre-trained NLP model.[108][109]

Considering the three AI options for the plant care assistant, each has its strengths, but the best choice for this project would be pre-trained NLP models. Pre-trained models, such as GPT or BERT, are specifically designed for natural language processing tasks and can understand and respond to user queries with impressive accuracy and fluency. The primary advantage of using pre-trained models is the ease of integration—they are ready to use out-of-the-box, saving time and resources on development. While custom chatbots and voice-activated assistants provide more tailored experiences, they require more complex setup and might not be as specialized or accurate in understanding plant-related questions. Pre-trained models offer a good balance of cost-efficiency, high-quality responses, and quick integration, making them the ideal solution for providing users with the plant care information they need without the added complexity of building a system from scratch.

3.13.3.1 Pre-trained NLP Options

OpenAI's GPT models, including GPT-3 and GPT-4, are among the most powerful and widely used pre-trained language models available. They excel at understanding and generating human-like text, making them an excellent choice for building a

conversational plant care assistant. With the ability to understand complex queries and provide detailed, coherent responses, GPT-3/4 can handle a wide range of questions, from basic plant care tips to more advanced troubleshooting. These models can be easily integrated via an API, which simplifies the development process and speeds up deployment. For our project, GPT-3/4's ability to generate personalized and context-aware responses will enhance the user experience, making it feel like a natural conversation. Its flexibility in handling diverse topics and adapting to specific needs makes it a strong candidate for our plant assistant, offering a seamless and engaging way to interact with users.[104]

Google's BERT (Bidirectional Encoder Representations from Transformers) is a pre-trained language model designed to understand the context of words in sentences by considering both the words before and after a target word. This bidirectional approach allows BERT to be highly effective in tasks like question answering, making it a great option for a plant care assistant. By using BERT, the assistant can better understand plant-related queries and retrieve the most relevant information from a database or pre-defined knowledge base. BERT's focus on understanding user input rather than generating responses makes it ideal for building a question-answering system that can provide quick, accurate answers to common plant care issues. It also excels at handling more specific, factual inquiries, ensuring that users get reliable and helpful advice about their plants.[105]

Rasa is an open-source conversational AI framework that focuses on natural language understanding and dialogue management. Unlike other pre-trained models, Rasa allows for greater control over the conversation flow, making it a solid option if you want a chatbot that follows specific rules or needs to handle complex interactions. With Rasa, you can train a model on plant-specific data, enabling the assistant to recognize intents (like "How do I water this plant?") and provide contextually relevant responses. Rasa is particularly useful if you want to create a more personalized plant care assistant that can engage in ongoing conversations, track past interactions, and improve over time. While it may require more development effort than other pre-trained API models, Rasa's flexibility and customization options make it an excellent choice for a tailored user experience, especially if you need more control over how the assistant responds to user queries.[107]

For our plant care assistant, OpenAI GPT-3/4 would likely be the best option. The model's ability to generate human-like, context-aware responses makes it an ideal choice for creating a natural, conversational AI experience. GPT-3/4 excels at understanding complex queries and providing detailed, helpful responses, which is essential for the variety of questions users may have about their plants. It is also highly adaptable and easy to integrate via API, streamlining the development process and allowing us to focus on other aspects of the project. While other options like Google BERT or Rasa are more specialized in tasks like question answering or structured conversations, GPT-3/4 offers the best balance of flexibility, performance, and ease of integration, making it the most suitable for providing an engaging and dynamic plant care assistant.

Feature	OpenAI GPT-3/4	Google BERT	Rasa
Type of Model	Transformer-based, generative	Transformer-based, bidirectional	Open-source, rule-based + ML
Main Strength	Generates human-like, context-aware text	Excels at understanding context and meaning	Customizable and adaptable with intent-based approach
Customization	Highly flexible, requires API integration	Fine-tuning for specific domains	Full control for custom workflows
Ease of Integration	Easy via API, flexible for various use cases	Requires setup for fine-tuning	Requires more development for setup
Use Case	Conversational agents, Q&A	Question answering, sentiment analysis	Interactive chatbot, custom use cases
Cost	Input (Prompt) Tokens: \$0.01 per 1,000 tokens Output (Response) Tokens: \$0.03 per 1,000 tokens	Free, but requires infrastructure for fine-tuning	Free, but requires server hosting

Chapter 4: Standards and Design Constraints

The BioSense system is designed with a focus on safety, efficiency, and sustainability, aligning with modern engineering practices and environmental responsibility. By integrating modular hardware, solar-based power systems, and intelligent sensor feedback, we ensure robust plant care in a compact form factor. Core design constraints emphasize low power consumption, weather tolerance, and user-friendly interfacing, all while maintaining compliance with electrical safety standards, electromagnetic compatibility (EMC), and RoHS directives [42]. These constraints and standards informed every part of our hardware and firmware architecture, resulting in a system that is not only functional but also safe, modular, and built to last in semi-outdoor environments.

4.1 Standards

To ensure BioSense remains reliable and safe across diverse use cases, we implemented a range of best practices and de facto standards in electronics, communications, and environmental engineering. Safety was a key priority—our high-current subsystems like the WS2812B LED grow light and 5V submersible pump are isolated, fused, and MOSFET-controlled to prevent overheating or back-EMF damage. The step-down converters regulating voltage from the 2S battery pack (8.4V max) down to 5V and 3.3V are protected against thermal overload and overvoltage, contributing to a stable and safe electrical backbone. RoHS compliance was observed through the use of lead-free components and recyclable materials [42]. Environmental design principles were also applied, particularly in enclosure planning, with ingress protection (IP) and UV exposure mitigation in mind.

Modularity and expandability were key architectural goals. JST-XH connectors make it easy to replace components or reroute subsystems without desoldering, and most sensors communicate via the I²C bus, enabling future sensor additions with minimal firmware changes. The ESP32-WROOM, our main controller, supports Wi-Fi and BLE—allowing for future wireless expansions using Bluetooth GATT-compliant devices [31]. Reliable protocols like I²C and UART were selected for sensor communication, and power-hungry components were decoupled via separate buck converters to minimize ripple and EMI. Our system also prioritizes data integrity with proper grounding, shielding, and error-handling in software. Altogether, these design standards help ensure the system is not only functional but also maintainable and ready for scaling.

Energy efficiency and environmental sustainability guided our power strategy. A 10W solar panel charges a 2S (8.4V) Li-ion battery pack, regulated by buck converters optimized for thermal performance and low dropout. Power-intensive components like the LED strip and water pump operate in bursts, controlled via MOSFETs and relays with PWM timing. The ESP32 enters deep sleep modes when idle, and sensors are polled on staggered intervals to conserve power without sacrificing fidelity. Our materials and build practices also reflect our sustainability goals—using low-noise regulators, recyclable enclosures, and eco-conscious soldering practices. Together, these elements

make BioSense not just a smart system—but a responsible one, designed to coexist with the environment it monitors.

4.1.1 Sensors

When it came to selecting the sensors for BioSense, we didn't just look for whatever was popular—we had to think about accuracy, compatibility, and long-term stability. For light sensing, we used the VEML7700, TSL25911FN, and AS7341-DLGM. Each one brings something unique to the table: the VEML7700 gives us lux-level precision under typical indoor and outdoor lighting, while the TSL25911FN adds high dynamic range performance in bright conditions. The AS7341 really took it up a notch by giving us a full multispectral readout across multiple light channels, which is perfect for analyzing light quality and tuning the grow light system. We stuck with I²C-compatible sensors as much as possible, because it simplifies communication and keeps wiring neat [32][33][34].

Temperature and humidity monitoring were handled by the DHT11, which, while basic, gave us the reliability and low-power operation we needed. For soil moisture, we went with the v1.2 capacitive soil sensor instead of a resistive one since it's more accurate and doesn't corrode over time [35]. For water level sensing inside the reservoir, we chose the tried-and-true HC-SR04 ultrasonic sensor—it gives precise measurements and was easy to mount above the tank [36]. All sensors were chosen to work in sync with the ESP32's voltage and communication requirements, and we made sure to follow all datasheet guidelines when it came to voltage levels, timing, and protection. We also started thinking about long-term use early on, so we considered things like protective housing, water resistance, and where the sensors would be exposed to sun or moisture during real-world deployment.

4.1.1.1 Safety Standards

Safety wasn't just a checkbox for us—it was a constant part of every design discussion, especially once we started working with higher current components like the water pump and the LED strip. To handle the power safely, we used IRLZ44N MOSFETs for switching, which let us control high-current devices using low logic-level signals without stressing out the microcontroller [37]. These MOSFETs were rated well above our expected current levels and had proper heat sinking and flyback diode protections where necessary. The pump, for example, has the potential to backfeed voltage when shutting off suddenly, so that needs to be managed properly to avoid damaging the control circuitry.

The WS2812B LED strip was another component we had to treat with care. It draws up to 6A at full brightness, so we fused the power line and isolated it from other sensitive components. We also put it on a separate buck converter so that voltage ripple wouldn't mess with the ESP32 or sensors. The LM2596S-ADJ step-down converters we used have built-in thermal shutdown and current limiting, which gives an extra layer of protection [38]. For battery charging, we originally looked at the TP4056, but due to the higher voltage of our 2S pack (8.4V), it wasn't a good match. We switched to a more

appropriate balanced charger designed for 2S Li-ion cells, giving us safer and more reliable charging. We kept RoHS compliance in mind by selecting components with proper certification and planned to use sealed enclosures with IP-rated gaskets to protect against dust, moisture, and UV exposure. Every safety measure we added wasn't just for show—it was about making sure the system could run 24/7 without catching fire or frying itself [42].

4.1.2 Electrical and Communication Standards

BioSense is built around the ESP32-WROOM, which serves as the central controller for sensor data acquisition, decision-making, and actuation. The module's built-in Wi-Fi offers convenient OTA (Over-The-Air) firmware updates, and its BLE capabilities provide a path for future integration of wireless sensor nodes or mobile app connectivity using Bluetooth 4.0+ GATT/GAP profiles [31]. This future-ready design ensures we won't need a full hardware overhaul when we expand system features.

For communication with peripherals, the I²C protocol is the backbone of the sensor network. It allows us to connect multiple I²C-compatible devices—including VEML7700, TSL25911FN, AS7341-DLGM, and DHT11—using just two data lines (SCL/SDA), minimizing wiring complexity and PCB real estate [32][33][34]. Analog signals, such as those from the capacitive soil moisture sensor, are routed to the ESP32's ADC pins. For high-current actuation, such as the water pump, we replaced the mechanical 5V relay module with an IRLZ44N logic-level N-channel MOSFET. This solid-state switching solution is more compact, efficient, and responsive, enabling safe control of the 5V submersible water pump directly via a digital GPIO pin [37]. The MOSFET is equipped with a gate resistor, flyback diode, and heatsink where necessary to prevent back-EMF, reduce thermal stress, and ensure reliable operation. Power management for the entire system follows proper switching regulator design practices, using LM2596S-ADJ modules to provide stable 3.3V and 5V rails with minimal ripple, dropout, and heat generation [38].

4.1.3 Energy and Environmental Efficiency

One of the biggest goals of BioSense was to make it energy-efficient enough to operate fully off-grid, and that meant putting a lot of thought into how power gets used, stored, and conserved. Our system is powered by a 10W solar panel, which feeds into a 2S 8.4V Li-ion battery pack. From there, we use LM2596 buck converters to step the voltage down to 5V and 3.3V depending on the component [39]. These converters were selected not just for their reliability, but also because they're efficient even when the battery voltage starts to dip. Every major part of the circuit—ESP32, sensors, lights, pump—was isolated onto its own voltage rail where needed to avoid brownouts or voltage drops caused by sudden current spikes.

Power-hungry components like the LED strip are set to run on timers, and their brightness is modulated using PWM so we're not running them at full blast all the time. On the firmware side, the ESP32 enters deep sleep mode between sensor reads, which can cut down current draw drastically when the system is idle. Sensor polling intervals

are staggered, with high-priority sensors (like soil moisture) checked more often than others, and the pump only activates when needed. We also tried to think green when it came to materials—we went with recyclable modules and lead-free solder where possible, and tried to keep the board size minimal to reduce e-waste. Every decision here was made with the idea that this system shouldn't just be smart—it should also be something we could feel good about putting into the world [42].

4.2 Design Constraints

Design constraints play a pivotal role in guiding both hardware selection and firmware architecture for BioSense. These limitations stem from the realities of power management, budget, physical conditions, and the need for consistent performance in semi-outdoor environments. Rather than view these constraints as setbacks, we approached them as design challenges that helped refine the system to be more efficient, resilient, and scalable. By addressing each constraint early in the design process, we ensured the resulting system was functional, safe, and deployable in diverse urban agricultural contexts.

4.2.1 Power Constraints

Power and safety constraints were among the most pressing design considerations, especially due to the use of a high-current LED strip (up to 6A at 5V) and a submersible pump. The limited energy budget imposed by a 10W solar panel and 2S battery pack meant each component had to be power-conscious and designed for intermittent operation. Safety-wise, all power electronics needed current protection, thermal regulation, and surge tolerance. We implemented IRLZ44N MOSFETs for switching, thermal-protected LM2596S buck converters, and integrated fuses on the main power rail to safeguard against overheating, voltage spikes, and component failure [44].

4.2.2 Economic/Budget Constraints

From the start, BioSense was developed with a student-budget mindset, aiming for affordability without compromising on core performance. We sourced open-source, widely available components like the ESP32-WROOM, VEML7700, and LM2596S to minimize cost while maximizing community support and integration flexibility [47]. Inexpensive yet reliable modules—such as the v1.2 capacitive soil moisture sensor and HC-SR04 ultrasonic sensor—allowed us to meet functionality targets within a \$100 prototype budget cap.

By using JST-XH connectors and modular plug-in design, we ensured repairability and future upgrades wouldn't require full system replacements. Our PCB layout was optimized to reduce board size and fabrication costs. Choosing passive cooling instead of active fans also cut material and power costs while avoiding mechanical points of failure [48].

4.2.3 Structural, Heat, and Environmental Constraints

BioSense needed to operate in semi-outdoor environments, meaning structural durability and heat management were essential. Enclosures had to shield sensitive electronics from UV exposure, water ingress, and debris. We used sealed ABS or polycarbonate housings with rubber gaskets rated to at least IP54 to mitigate dust and moisture ingress [49]. High-heat areas like the MOSFETs and LED power converters were isolated in the enclosure and provided with aluminum heat sinks and ventilation slots to manage thermal buildup.

The plant reservoir and pump also posed design challenges in terms of splash protection and corrosion resistance. Mounting the ultrasonic sensor above the waterline and encasing wiring in silicone sleeves helped address these constraints. These measures allowed us to maintain system performance over extended periods, even in humid or partially sun-exposed locations [50].

For the enclosure materials, we selected rigid thermoplastics such as PETG or polycarbonate blends suitable for 3D printing. These materials offered sufficient mechanical strength and thermal stability to handle indoor conditions, including localized heat buildup from LED arrays and switching components. The LED strip, capable of drawing up to 6A at 5V, along with the MOSFETs and step-down converters, could generate concentrated thermal zones. To account for this, structural elements around heat-critical regions were thickened slightly and incorporated passive ventilation features such as finned slots and underbody airflow gaps. These minor adjustments improved thermal dissipation without requiring active cooling or sacrificing form factor.

The electronics compartment, housing the ESP32 board, battery, converters, and relay, was placed in a watertight middle section shielded from the plant and reservoir areas. We employed internal mounting pillars and sliding trays to hold the PCB securely, minimizing vibration and protecting sensitive solder joints. Since the reservoir would be occasionally refilled, the divider between the water bay and electronics was sealed with EPDM gaskets, and wiring between compartments was routed through dedicated conduits with silicone sleeving. This allowed the structure to remain serviceable while maintaining environmental isolation between wet and dry zones.

The pot's modular design also simplified maintenance and fabrication. 3D-printed components could be iterated quickly, and support structures were designed with snap-fit features and bolt mounts compatible with common M3 hardware. Structural infill patterns were adjusted to provide additional internal rigidity in high-load areas without excessively increasing print time or material use. These choices ensured the BioSense housing was durable enough for indoor or semi-outdoor deployment while being flexible for prototyping and future modifications.

4.2.4 Light Sensor Constraints

The light sensors—VEML7700, TSL25911FN, and AS7341-DLGM—were core to monitoring light intensity and quality, but each came with specific constraints. Most light sensors are designed for stable indoor lighting, so ensuring proper angular placement and shielding from direct sunlight was critical. Spectral sensors like the AS7341 are especially sensitive to IR contamination and need UV-resistant diffusers or shaded enclosures to avoid skewed readings [51].

Additionally, I²C communication limited cable length and required tight shielding and grounding practices to avoid noise from the PWM signals of the grow light. Firmware-wise, polling frequency had to be balanced with power consumption and sensor warm-up time to avoid unnecessary wake cycles on the ESP32. We calibrated sensors under controlled conditions and applied digital averaging to smooth data for light-based actuation decisions [52].

4.2.5 Safety Constraints

Safety was addressed both in terms of electrical design and physical interaction, particularly given the system's proximity to water and soil. All high-current lines were fused or routed through protective switching elements like relays or MOSFETs with flyback diodes where inductive loads were present. The water pump and lighting circuits were electrically isolated from the control side via opto-isolated or relay-based switching to prevent backflow of current into sensitive components. Battery management included overcharge, over-discharge, and short-circuit protection circuits, ensuring safe operation even during user error or abnormal conditions. Connectors were keyed and labeled to prevent incorrect installation during maintenance or assembly.

From a structural perspective, all internal wiring was routed through silicone sleeves and strain-relieved at entry points to prevent chafing or accidental disconnection. The electronics bay was made tamper-resistant and only accessible through screws to limit unintended user contact with live circuitry. Heat-generating components like the MOSFETs and regulators were placed away from plastic walls and mounted with thermal interfaces to aluminum sinks, reducing the risk of thermal deformation or burns. Additionally, the entire system was tested for over-temperature and overcurrent events under simulated fault conditions. These precautions were essential in making BioSense safe for long-term indoor use, even in environments with moisture, heat, or variable handling.

4.2.6 Water Management and Leakage Control

Given that BioSense incorporates an active watering system and a built-in water reservoir, water management became one of the most critical design constraints. Even small leaks or condensation could lead to system failure if moisture reached the PCB or battery compartment. To mitigate this, the reservoir was structurally isolated from all electronics, with physical barriers between compartments and sealed pass-throughs for

pump tubing and sensor wiring. All entry points for cables were grommet and sleeve with silicone tubing, and where possible, we added strain relief to reduce wear from movement or vibration. The ultrasonic water level sensor was mounted on an internal bracket above the waterline, keeping it safe from splashes while still providing reliable measurements.

We also designed the enclosure with passive safety features in mind. A sloped internal geometry in the electronics bay allows any accidental moisture ingress to drain away from sensitive components, and we reserved space for an optional leak detection pad or moisture sensor under the PCB for future iterations. Additionally, pump control logic was configured with timing limits to prevent prolonged or runaway activation, and the soil moisture thresholds were software-limited to avoid overwatering. These steps helped ensure that water delivery remained efficient without compromising the electronics or structural integrity of the system.

4.2.7 Maintenance and Modularity Constraints

Because BioSense is intended for long-term use in a semi-autonomous indoor setting, ease of maintenance and modularity were built into the core design. The enclosure was split into three functionally isolated sections — one for the soil and plant, one for electronics, and one for the reservoir. Each section is accessible independently, reducing the need to disturb the entire setup when servicing individual components. The electronics tray slides out on printed rails and secures with M3 screws, allowing quick access to the ESP32, battery, and converter modules without having to disconnect the entire system. Plug-and-play JST or B3B-XH-A connectors were used for all internal wiring to support fast replacement or swapping of sensors and modules during prototyping or field maintenance.

We also prioritized reusability and iteration by making most structural components 3D-printable and bolted together, not glued. This allowed us to experiment with different enclosure geometries and modify the layout as new features were added. The reservoir was designed with a removable cap for easy refilling and cleaning, while the soil compartment could be detached from the rest of the unit for transplanting or potting changes. These modular decisions not only helped during development and testing but also made the system more user-friendly and serviceable for non-technical users or in educational environments.

4.3 Optimizing with Power Supply Integration

A key innovation in BioSense was the power-aware integration of sensor polling and actuator control, enabling responsive plant care without excessive energy usage. The timing and control logic were tightly coupled to the battery's state and solar charging cycles. The system staggered sensor reads and prioritized soil moisture and ambient light checks to determine if watering or light adjustment was needed. High-draw

components like the LED grow light only activate during low ambient light and follow preprogrammed photoperiods controlled via PWM.

ESP32's deep sleep feature drastically reduced idle current draw, and sensors were polled at varying frequencies depending on environmental stability. This allowed the plant-care logic to remain active while preserving battery life, especially on cloudy days or during indoor testing [53]. Such integration of energy feedback into care algorithms reflects the project's goal of sustainable automation.

4.3.1 Power Supply Implementation

The final power supply design combined a 10W 5V solar panel, a balanced 2S Li-ion battery pack (8.4V max), and two LM2596S buck converters to produce stable 5V and 3.3V rails [44]. A dedicated power rail served the high-current WS2812B LED strip, while other peripherals like sensors and the ESP32 shared a separate, filtered supply. We selected the LM2596S due to its efficiency, thermal shutdown, and adjustable output, which allowed fine-tuning of each voltage rail based on real-world measurements.

Current draw was monitored during both idle and peak states to ensure battery discharge remained within safe depth-of-discharge limits. USB power was retained for fallback use or firmware debugging. The modular power architecture also allows future upgrades like MPPT solar chargers or higher-capacity batteries without overhauling the entire board design [54].

4.4 Water Resistance and Waterproofing

In the BioSensePot project, the role of water resistance is crucial for the long-term reliability and efficient operation of the system. Given the presence of moisture from automated watering, humidity variations, and potential water splashes, water-resistant components help protect sensitive electronics from exposure to damaging elements. For example, the ESP32 microcontroller, transistor, and LCD screen, though not directly exposed to water, benefit significantly from an IP64 or IP65 rating. These ratings ensure protection against dust and splashes, reducing the risk of water ingress while still allowing for reliable performance. On the other hand, components such as the ultrasonic water level sensor and the mini submersible pump must be able to endure harsher conditions, with an IP68 rating being ideal for the pump to handle full submersion without failure. Selecting the right level of water resistance for each component ensures that the BioSensePot remains robust, even in environments with high moisture levels, maintaining its efficiency and preventing damage.

4.4.1 Water Resistance

Water resistance, on the other hand, is sufficient for components that are not directly exposed to water but may encounter humidity, condensation, or occasional splashes. The ESP32 microcontroller, MOSFET, and charging module do not require full waterproofing but should be protected against moisture ingress to prevent short circuits and corrosion. Applying a conformal coating to the ESP32's circuit board can help protect it from humidity, while placing it within a well-ventilated but moisture-sealed

enclosure further ensures longevity. Similarly, the transistor module, which switches power to different components, is vulnerable to oxidation if exposed to excessive humidity. Housing the transistor within an IP65-rated enclosure would provide adequate dust protection and shield it from water splashes. The spectrometer, a sensitive optical component used for plant health analysis, also benefits from water resistance rather than full waterproofing. Since direct exposure to water could interfere with its readings, a controlled humidity environment with protective lens coatings would help maintain its accuracy.

4.4.2 Waterproofing

Waterproofing plays a crucial role in ensuring that key components of the BioSensePot project remain fully functional even in direct water exposure. Certain components, such as the 5V mini submersible water pump, require a high level of waterproofing since they are designed to operate while fully submerged. A submersible pump must meet at least an IP68 rating, meaning it is completely dust-tight and can withstand continuous immersion in water beyond one meter under specified conditions. This level of protection is critical to prevent electrical failure due to water infiltration, ensuring that the pump operates reliably over time. In contrast, the solar panel, although exposed to environmental moisture, typically requires an IP67 rating, which offers full dust protection and the ability to withstand temporary immersion in water up to one meter deep. This level of waterproofing ensures that rain or accidental splashes do not compromise its electrical integrity, while its sealed edges and encapsulated photovoltaic cells provide additional protection against prolonged exposure to moisture.

4.4.3 IP Rating system

The Ingress Protection (IP) rating system is a standardized way to classify the degree of protection that electrical enclosures provide against solid objects (such as dust) and liquids (such as water). The IP rating is typically written as IPXX, where the first digit (X) indicates the level of protection against solid objects and the second digit (X) represents the level of protection against liquid ingress.

First Digit (Solid Protection)	Description	Second Digit (Water Protection)	Description
0	No protection against solid object	0	No protection against water
1	Protected against solid	1	Protected against vertically falling water droplets

	object >50mm		
2	Protected against solid object >12.5mm	2	Protected against dripping water at 15 degree angle
3	Protected against solid object >2.5mm	3	Protected against dripping water at 60 degree angle
4	Protected against solid object >1mm	4	Protected against water splashes from any direction
5	Limited dust protection (some ingress allowed, but no damage)	5	Protected against low pressure water jets (6.3mm nozzle).
6	Fully dust-tight	6	Protected against strong pressure water jets (12.5mm nozzle).
6	Fully dust-tight	7	Protected against temporary immersion in water (1m depth for 30 minute)
6	Fully dust-tight	8	Protected against continuous submersion in water (manufacturer-defined depth and duration).
6	Fully dust-tight	9k	Protected against high pressure, high temperature water jets.

Most of the components in the BioSensePot project require a high level of water resistance to ensure durability and reliable performance in an environment where moisture is constantly present. Since the system involves automated watering, humidity variations, and potential water splashes, components like the ESP32 microcontroller, relay module, spectrometer, and charging module must be well-protected from water exposure. These electronics do not require full waterproofing but benefit from at least an IP64 or IP65 rating, which ensures dust-tight protection and resistance against splashes or low-pressure water jets. By housing these components in a sealed enclosure and using conformal coating on circuit boards, we can further enhance their water resistance and prevent damage due to condensation or accidental exposure.

However, certain components that come into direct contact with water require higher IP ratings to function reliably under submerged conditions. The 5V mini submersible water pump, for instance, must have an IP68 rating, ensuring full dust protection and

continuous submersion without failure. The solar panel, although not submerged, must withstand outdoor conditions, including rain and humidity, making an IP67 rating ideal to prevent water ingress. Similarly, the grow light needs at least an IP65 rating, protecting it from dust and water splashes, ensuring safe operation even in high-humidity conditions. By selecting the appropriate IP ratings for each component, the BioSensePot system maintains long-term reliability and efficiency in an environment where water exposure is inevitable.

Chapter 5: Large Language Model Usage

In the BioSensePot project, the Large Language Model (LLM) plays a crucial role in building the coding structure, debugging issues, and ensuring that all components are compatible with one another. By leveraging the model's ability to analyze code and system architecture, it helps identify potential integration issues and suggests ways to improve the overall design. The LLM can also assist in generating step-by-step checklists for the project, outlining essential tasks, milestones, and testing procedures, ensuring that each phase progresses smoothly. Additionally, by offering design recommendations based on best practices, the LLM helps streamline decision-making and reduces the likelihood of errors during development, enhancing the overall efficiency of the project.

5.1 AI overview

For our senior design project, which focuses on developing a smart plant pot, we need an AI platform that can assist with debugging code, provide in-depth knowledge on electronic components, and suggest research-backed improvements. AI tools can be invaluable in troubleshooting sensor integration, optimizing power management, and refining automation algorithms. In this section, we compare different AI platforms to determine which one best supports our engineering and development process.

5.1.1 ChatGPT

ChatGPT has proven to be an invaluable tool for engineering projects like our BioSensePot. It excels at debugging code, helping us quickly identify errors in our ESP32 firmware, sensor scripts, and automation logic. Beyond just fixing bugs, ChatGPT explains coding concepts, making it easier to understand how different algorithms work, which is crucial when fine-tuning our system.

Additionally, ChatGPT helps us understand electronic components in-depth. Whether it's researching the power efficiency of Li-Po vs. Li-ion batteries, exploring sensor accuracy, or learning about optimal soil moisture levels for plant health, ChatGPT provides detailed explanations and practical recommendations.

Another key advantage is its ability to suggest alternative components. If a sensor we planned to use is unavailable or too costly, ChatGPT offers similar alternatives, comparing their pros and cons so we can make the best decision for our project.

5.1.2 Perplexity AI

As a way to ensure that we are working with valid and scholarly sources, we have integrated Perplexity AI into our research process to gain a deeper understanding of engineering problems and technical concepts. By using Perplexity AI, we are able to search for credible sources, including peer-reviewed papers, academic journals, and technical reports, which allows us to gather accurate information that supports our project. The focus of this approach is to enhance our ability to find relevant research efficiently while ensuring that the sources we rely on are reputable. Using Perplexity AI, we are able to cross-reference multiple sources and extract key insights that contribute to our engineering decisions. This process allows us to develop a well-rounded understanding of the problem, ensuring that we are basing our solutions on scientifically validated data rather than assumptions.

In order to verify and compare the information we obtain, we have also incorporated ChatGPT as a secondary resource to summarize and interpret complex technical details. While Perplexity AI provides direct access to academic sources, ChatGPT allows us to better understand the context and application of these findings in relation to our project. By comparing the results from both tools, we are able to validate the credibility of our research and ensure that our engineering solutions align with industry standards. The objective of using both platforms is to identify the most effective approach for problem-solving, considering factors such as accuracy, reliability, and ease of application. Through this method, we are able to create an engineering framework that is both evidence-based and practical, ensuring that our project is built on a strong foundation of verified research and analysis.

5.2 AI utilize in project

For our engineering project, we need an AI platform that not only helps with research but also assists with debugging, component selection, and system optimization. After careful evaluation, ChatGPT is our primary AI tool since it provide us:

- Debugging support: Helps analyze and fix ESP32 firmware, sensor readings, and power management logic, reducing development time.
- Deep component knowledge: Explains the behavior of sensors, batteries, pumps, and microcontrollers, helping us make informed design choices.
- Research suggestions: Recommends alternative sensors, better battery technologies, and optimization techniques to improve our system's efficiency.
- Code optimization: Suggests better algorithms for water level detection, soil moisture analysis, and energy-saving techniques.

As a way to ensure that we select the most suitable components for our BioSense Pot project, we have used ChatGPT to research different types of water pumps, sensors, and electronic components that align with our design requirements. Since the system involves monitoring environmental factors such as temperature, moisture, and light intensity, we needed to explore the different types of sensors available and determine which ones would be the most accurate and efficient. By asking ChatGPT about various sensor types, including capacitive moisture sensors, thermistors, and photodiodes, we were able to understand their operating principles and compare their performance based on response time, accuracy, and compatibility with our microcontroller. Additionally, we explored different types of water pumps, such as peristaltic and submersible pumps, to identify the most effective option for controlled water delivery to our plants.

To ensure that all components within the BioSense Pot are properly connected and function without electrical conflicts, we used ChatGPT to analyze the compatibility between sensors, power sources, and control units. Knowing that voltage and current draw are critical factors, we asked ChatGPT to help calculate power consumption and determine whether our battery and solar panel could sustain the system efficiently. We also needed to verify that our microcontroller could handle multiple sensor inputs without exceeding its operational limits. By providing specific technical details, such as operating voltage ranges and current requirements, ChatGPT allowed us to assess the feasibility of our design before assembling the hardware. This helped us avoid potential issues related to power mismatches or data communication errors between components.

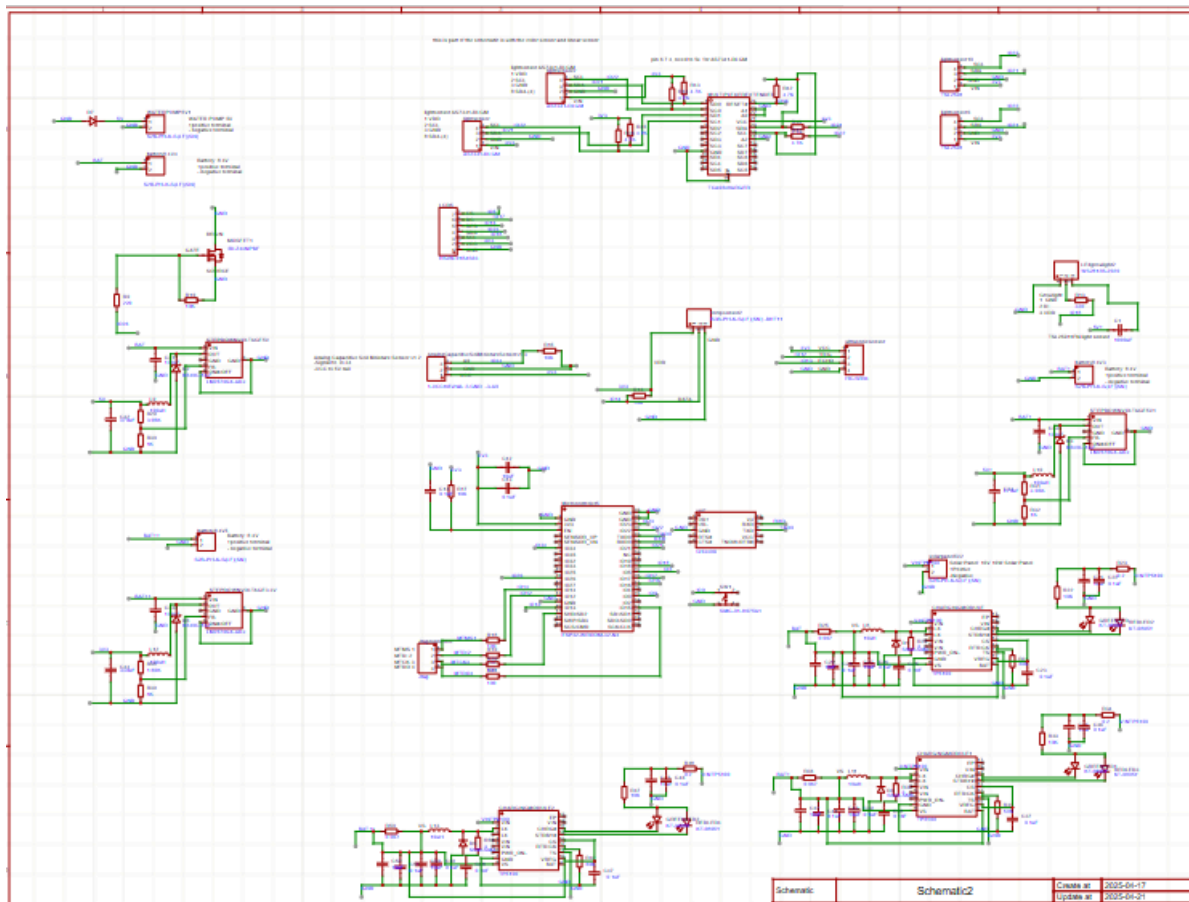
Since our project requires integrating electronics with a water-based system, ensuring water resistance and component protection was a major concern. We used ChatGPT to research different methods of waterproofing electronic components, including conformal coatings, silicone sealants, and waterproof enclosures. By analyzing the pros and cons of each method, we were able to identify the best approach for protecting our sensors and circuits from moisture exposure while maintaining accessibility for maintenance. Additionally, we explored insulation techniques to prevent short circuits and corrosion over time, ensuring the long-term reliability of the system. ChatGPT also provided insights on using protective casings and placement strategies to minimize direct exposure to water, further improving the durability of our design.

To verify and supplement the information obtained from ChatGPT, we used Perplexity AI to find credible sources, including scientific research papers, engineering blogs, and manufacturer datasheets. By cross-referencing the technical specifications and recommendations provided by ChatGPT with academic and industry-backed sources, we were able to ensure the accuracy of our design choices. This allowed us to confidently select sensors and components that met our project requirements while maintaining efficiency, durability, and reliability. Through this dual approach, we not only gained a solid understanding of the necessary components but also ensured that our BioSense Pot system would function optimally under real-world conditions.

Chapter 6: Hardware design

This schematic represents an automation and monitoring system for smart plants that can be used to grow healthier plants without the continuous need for manual attention. This system is designed for the purpose of automatically monitoring and managing a plant's environment, including watering, light levels, and sensor feedback, using a network of electronics controlled by a microcontroller that is connected to a network of sensors.

6.1.1 Overall schematic:



6.1.2 Microcontroller

Now we will be going over a portion of the schematic which gives us a deep understanding of how our project is able to function, and how it helps grow our plant, by giving an insight into some of the major components. It will describe in more detail what makes up this system, including the sensors that monitor environmental conditions, the microcontroller that processes and controls the data, and the network of electronics that

enable communication and automation to take place. There are a number of components that work together to ensure that the plant's environment is as optimal for growth as possible.

In ESP32-WROOM-32, the ESP32-WROOM-32 serves as the main processor and communication hub for this system, orchestrating all sensor readings, decision-making, and output control through the ESP32-WROOM-32. In addition to featuring a powerful, low-power microcontroller module with built-in Wi-Fi and Bluetooth, this module is also suitable for smart monitoring and IoT applications. In this project, the ESP32 gathers real-time environmental data from various sensors, including two AS7341 spectral color sensors, a TSL2591 high-range lux sensor, and a VEML7700 ambient light sensor, all of which are connected using the I2C communication protocol to provide real-time data. The ESP32 uses the TCA9548A multiplexer to communicate selectively with multiple I2C devices that have duplicate addresses, allowing it to selectively communicate with each sensor on different I2C channels, allowing it to manage multiple I2C devices with duplicate addresses. A soil moisture sensor is also used to determine the soil's water level by reading analog data from a soil moisture sensor.

The ESP32 uses its digital output pins to trigger MOSFET switches based on sensor readings, in order to control peripheral devices such as the WS2812B addressable grow light LED strip and the 5V submersible water pump via its digital output pins. It also sends data to a 0.96" SPI OLED display, which provides live feedback, such as moisture percentage or light intensity. A 3.3V step-down voltage regulator is used to control the voltage output of the ESP32, ensuring that it gets a steady supply from the main battery input (7.4V from a 2S lithium pack). Incoming data is processed by the ESP32, which runs the core program logic and makes decisions automatically, such as turning on the light when ambient light levels are low or activating the water pump when the soil is dry.

Figure: ESP32-WROOM BLOCK DIAGRAM

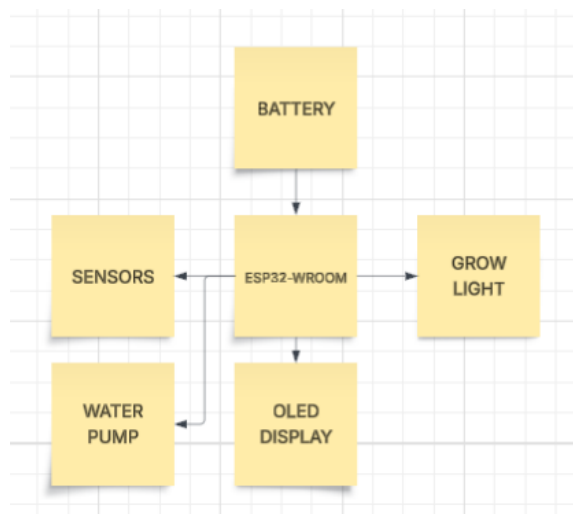
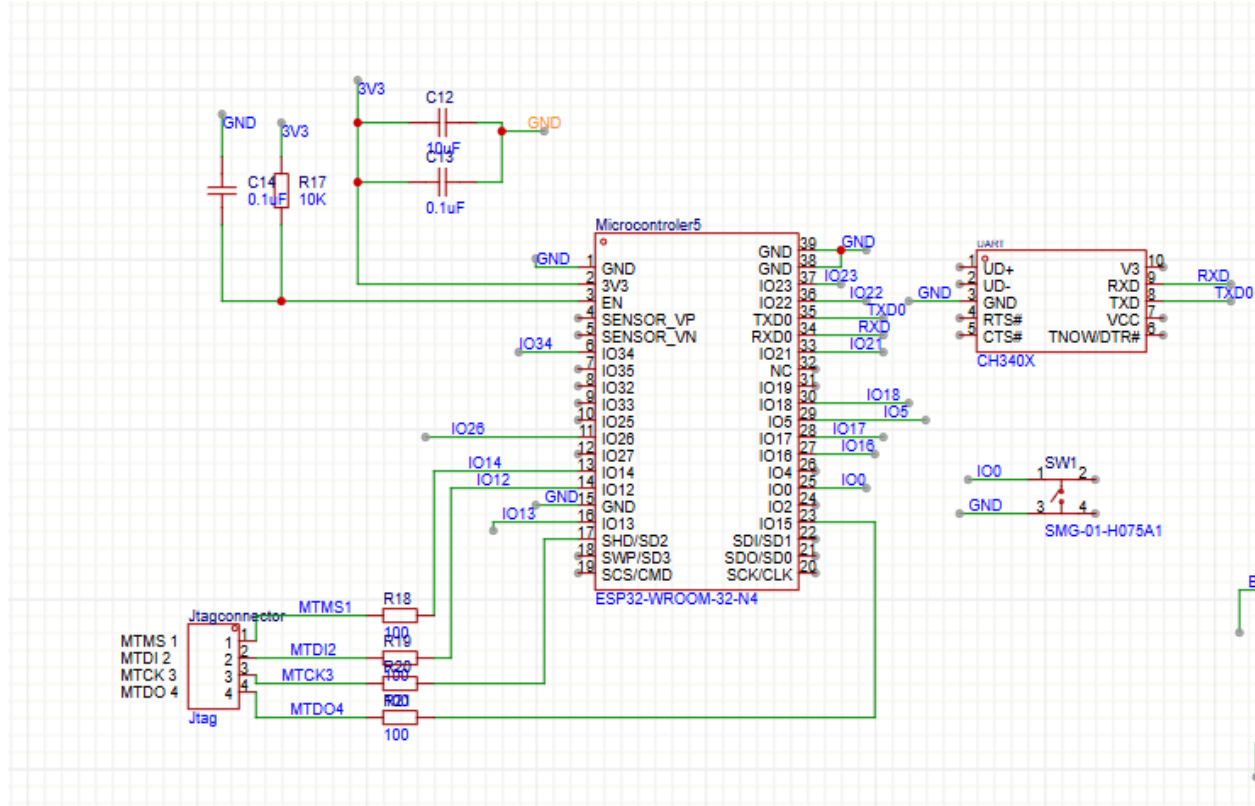


Figure: Schematic



6.1.3 Multiplexer

In this hardware system, the TCA9548A I2C multiplexer is a vital component that enables the ESP32 microcontroller to communicate with a large number of I2C devices that share the same address, such as the two AS7341-DLGM light sensors, which are used for spectral analysis, using one address. Multiple devices can be connected to the same SDA (data) and SCL (clock) lines of the I2C protocol, but each device's address needs to be unique in order for them to communicate. It is important to note that because AS7341 has fixed I2C addresses, it would be impossible to connect them directly in parallel without causing an address conflict. By acting as a communication bridge, the TCA9548A is capable of resolving this issue: it has an I2C master interface (SDA, SCL) that is connected to the ESP32, as well as eight selectable downstream channels (SD0–SD7 and SC0–SC7), each of which can be activated individually through software commands sent over I2C.

In order for the ESP32 to communicate with a specific sensor, it must send a command to the TCA9548A in order to activate one of its channels (for example, channel 0 for AS7341 #1 and channel 1 for AS7341 #2). It is thus possible to isolate the other sensors from the bus, isolating them from each other and avoiding address conflicts as a result. The TCA9548A controls the operation of these channels via an internal control register located within the device. A pull-up resistor is placed on each I2C line (SDA and

SCL) in order to ensure that the voltage levels and communication integrity are maintained. There is a 3.3V supply for the multiplexer, and it shares a common ground with the ESP32 and the sensors so that the signals will remain consistent at all times.

FIGURE: Multiplexer block diagram

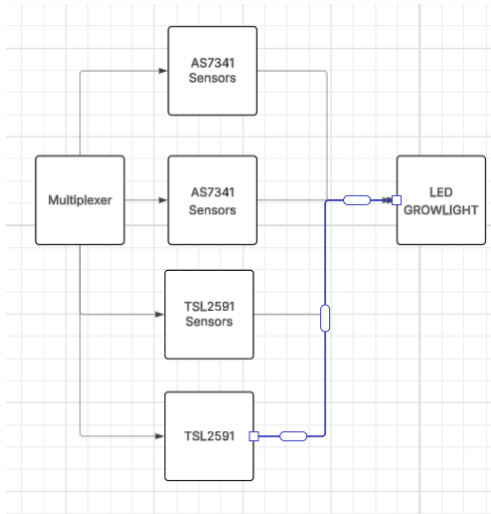
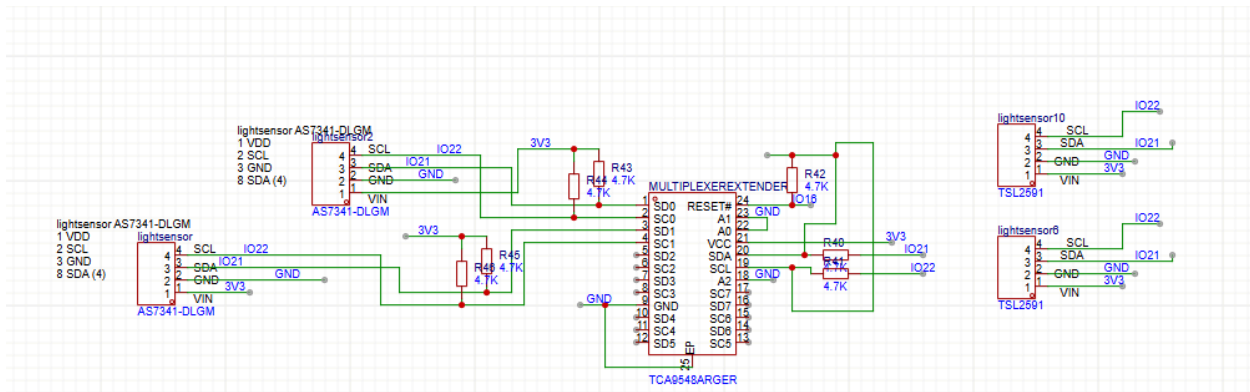


Figure:Schematic



6.1.4 Step down (buck) regulators

In order to ensure stable and appropriate power delivery to the components connected to the ESP32 microcontroller, the 5V and 3.3V voltage regulators play a crucial role in this hardware system. A step-down (buck) converter called the LM2576SX-ADJ is used in these regulators, which takes a higher voltage from the battery (up to 8.4V from a 2S lithium pack) and steps it down to either a voltage of 5V or a voltage of 3.3V, depending on the resistor divider network that is connected to the feedback (FB) pin on the battery. For devices like the WS2812B grow lights, which require higher currents and voltages for proper illumination, the 5V regulator is responsible for providing power. In contrast,

the 3.3V regulator powers sensitive logic components such as the ESP32-WROOM-32, sensors (such as AS7341, TSL2591, and VEML7700), and communication modules.

It is important to note that both regulators rely on an inductor (L), a Schottky diode (D), and filter capacitors (C) to smooth out the output voltage and minimize ripple, which is important for maintaining system stability and preventing noise from affecting sensor readings. As a result of the LC network, the LM2576SX ensures high efficiency even at higher currents by switching power rapidly and filtering the signal through the LC network quickly. The adjustable output is set by using the resistor network (R30 and R32 for 5V and R39 and R35 for 3.3V). The resistor network is calculated to match the reference voltage of 1.23V, and the output is adjusted accordingly. On/Off pins are grounding to ensure continuous operation, and input and output capacitors (100F and 330–470F), respectively, provide the system with the capability to handle transient responses and ensure reliability at startup. As a result of the regulation of voltages, the embedded system is able to provide steady power for various subsystems, enabling seamless operation of the sensors, control logic, and communication interfaces throughout the entire embedded system thanks to its stable backbone of voltages.

Figure: Two Step down regulator 5V and one 3V3 block diagram

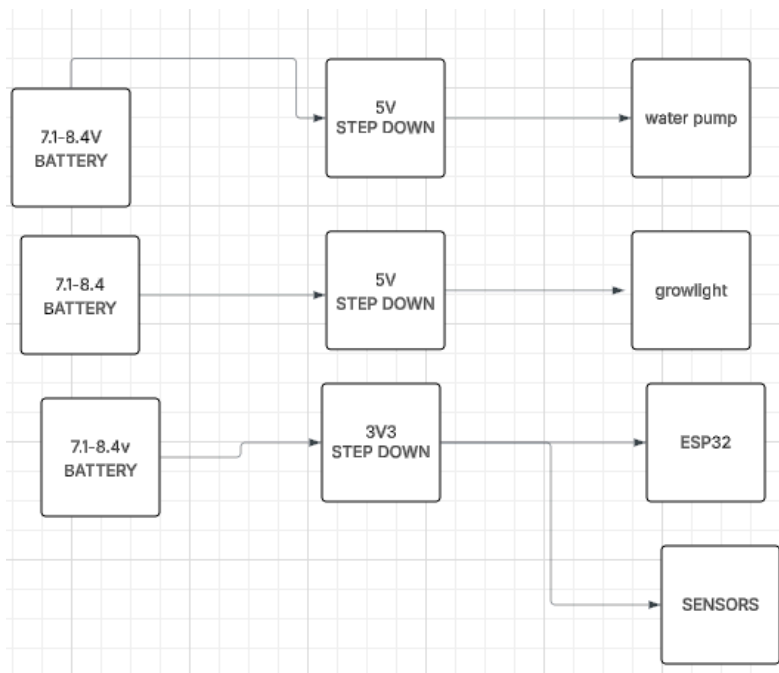
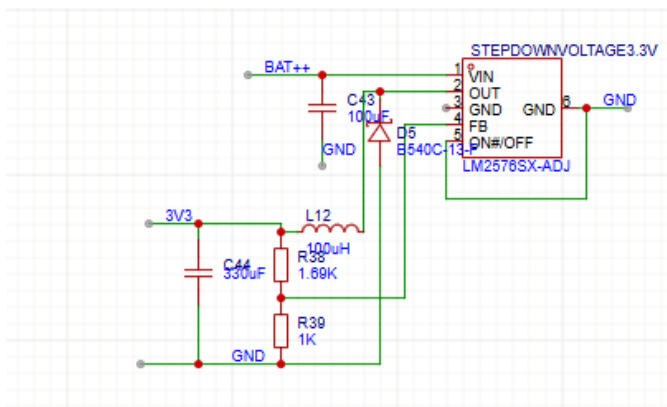
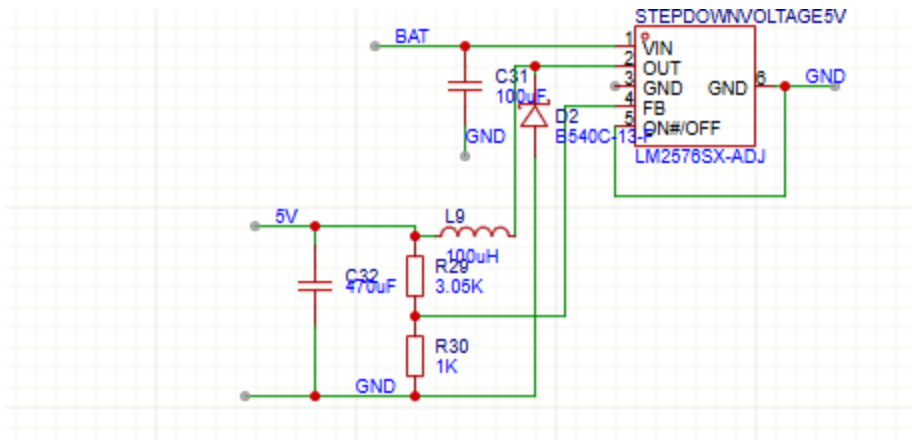


Figure: Schematic



6.1.5 Charging module

The TP5100 is a high-efficiency, dual-cell lithium battery charging IC that plays a crucial role in managing the power system for the smart plant monitoring project that is part of the project. It is designed specifically to charge two 2S (2 x 3.7V) lithium-ion batteries in series in order to ensure the batteries are charged safely and efficiently either with the help of a solar panel or with the help of a USB cable. This system uses a TP5100 as the charging module that receives power from the charging source and provides balanced charging current to the two cells of the battery pack, supporting a charging voltage of 8.4V and a charging current of up to 2A depending on the configuration.

Featuring a number of features such as overcharge protection, automatic recharge, thermal regulation, and battery disconnect detection, this IC is a perfect solution for applications like this plant pot that utilize solar power or are mobile. Additionally, the TP5100 can also be connected to a microcontroller, or alternatively, an LED to display the state of the charging process (via the STAT pin on the board). Switching regulation is used to reduce energy waste and heat in the system, which improves the battery life as well as the efficiency of the system. As soon as the battery is fully charged, the TP5100 shuts off the charging process and maintains the battery in a safe state until it needs to be recharged again.

Figure: Charger module block diagram

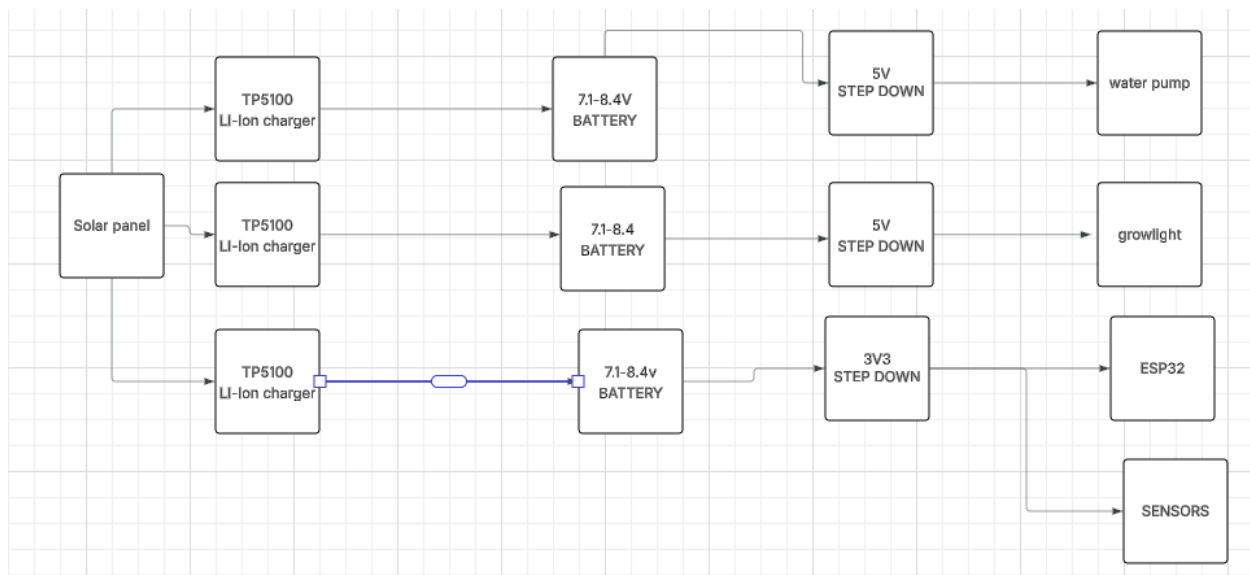
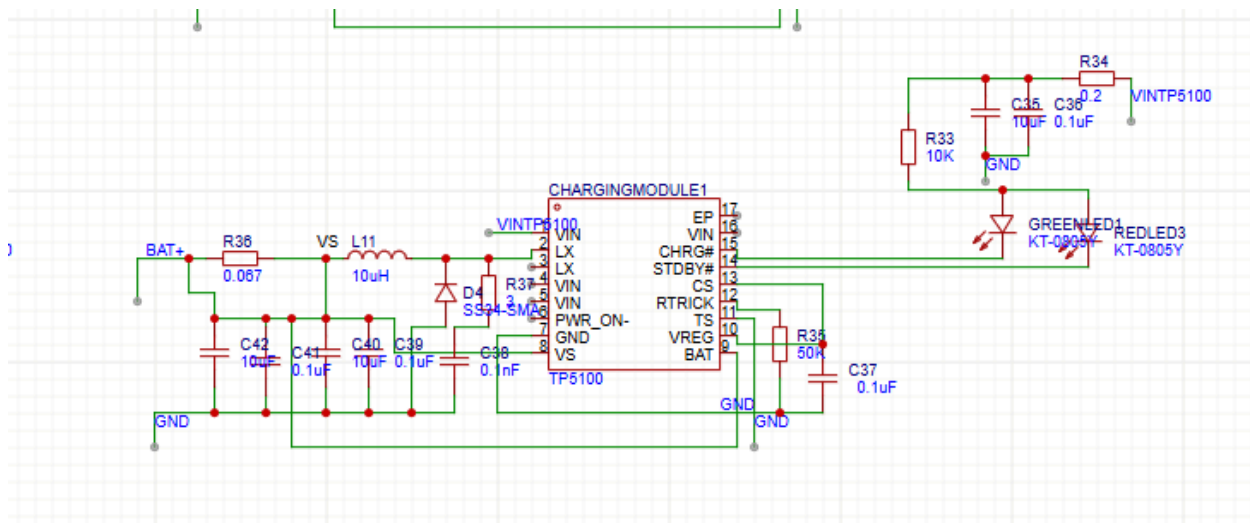


Figure:Schematic



6.1.6 Summary about schematic and PCB

It was necessary to plan and make careful decisions when designing the hardware for our smart plant pot system in order to ensure that everything worked efficiently, fit within the limited space, and was easy to test and replace. The first thing we did was organize our schematic in such a way that each resistor or support component would be close to the major component to which it belonged, which improved both the layout clarity and the signal integrity of the schematic. As a result of the complexity of the wiring structure, net labels were widely used to visually group related connections and simplify them. We were also able to spot and troubleshoot issues during the testing process by using this method.

It wasn't just about performance when we chose components, it was also about availability in the real world, affordability, and compatibility in terms of design. There were a number of parts that were not available in EasyEDA's library, so we matched Amazon bought components with similar specs from the platform, and adapted their footprints to fit within the EasyEDA library. For example, we often had to rotate, resize, or flip connectors like headers to ensure that everything was aligned properly during the soldering process. Sensor headers as well as the grow light interface needed to be replaceable.

Initially, we tried to use a step-up converter to provide the power, but it was not able to deliver the current that was required. As a result of our tests, we have made the decision to use two 3.7V Li-ion batteries in series (7.4V), as well as two step-down voltage regulators (LM2596S-ADJ) to deliver 5V and 3.3V voltages. ESP32 and logic-level devices were powered by the 5V rail, while the 3.3V rail powered the grow light, water pump, and sensors. Our goal was to ensure that the system operated cleanly and reliably at all times, which is why we added an indicator LED to the 3.3V rail. This LED helps visually confirm that the system is powered properly.

It was decided to use the TP5100 charging module in order to manage the safe charging of the 2S battery pack. When we first tested the charger, we found that connecting 7.4V directly into a TP4056 was causing shorting, which we fixed by regulating the voltage before feeding it into the charger. Having a good power distribution system, a grounding system, and a clear trace separation system became top priorities. It was discovered that common grounding is very important, especially when there are high-current components such as the water pump that cause noise or voltage instability in sensors due to high currents.

On the PCB, we arranged the ESP32 centrally as the center of control, and all components were arranged around it logically step-down regulators, pump MOSFETs (IRLZ44N), multiplexer (TCA9548A), and sensor headers. As a result of our design, every major component has its own functional space, so that we can test, replace, or expand the system with relative ease. Whenever components such as the AS7341, TSL2591, VEML7700, and the OLED display needed to be modular or swappable, female headers were used.

The ESP32 was able to accurately control the pump based on soil moisture level based on final tests, which showed improved system stability. MOSFET gate resistors and wiring were adjusted for improved system stability. The project not only taught us how to design a PCB, but also how to deal with real-world challenges such as grounding issues, pin mismatches, and voltage drop.

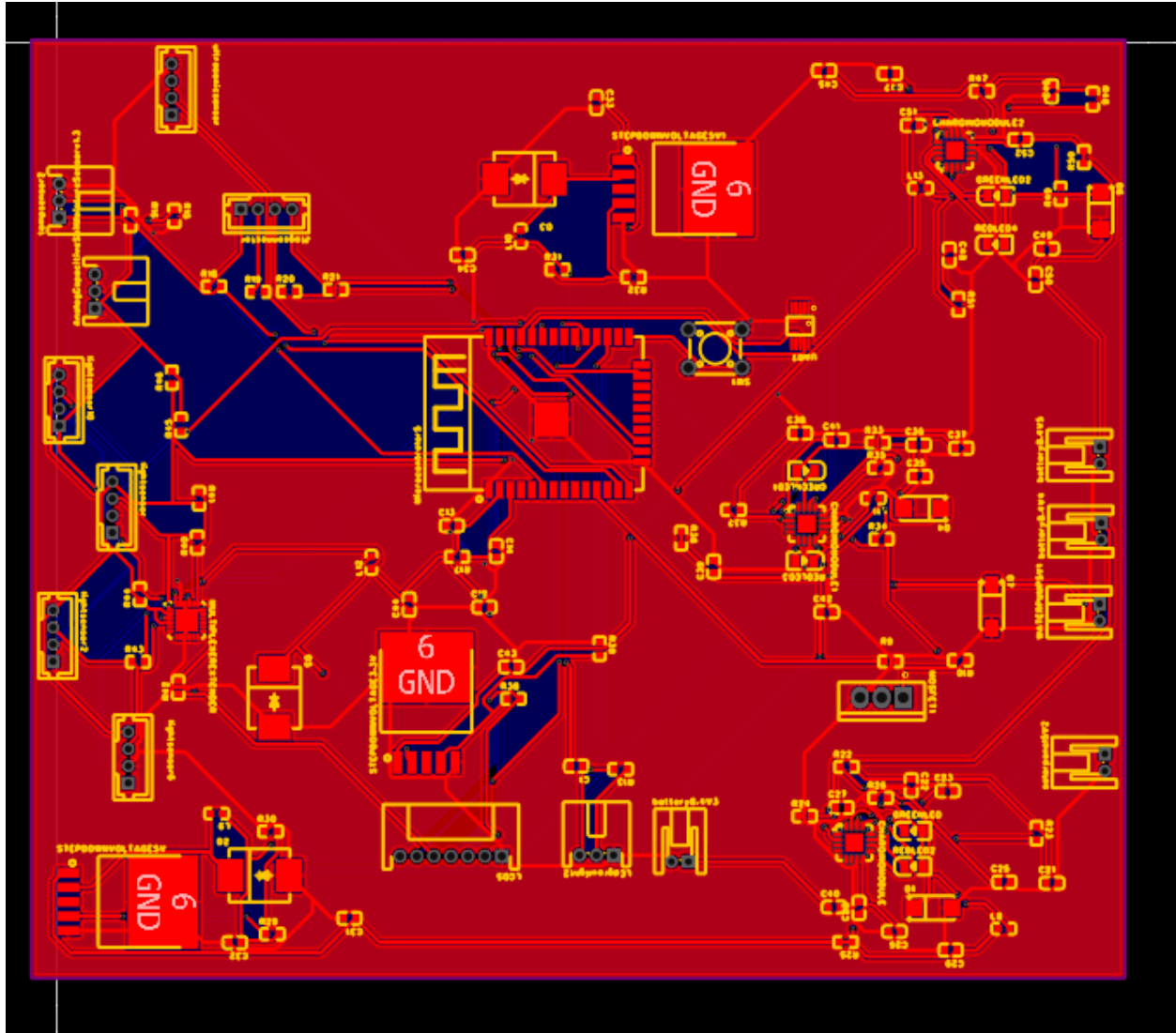


Figure 40: PCB design in EasyEDA software for Bio-Sense Pot project

6.10 Optical Hardware Design

The optical hardware design of the Bio-Sense Pot focuses on compact, non-imaging systems that capture and measure both internal and ambient light. Each subsystem is designed to fit within tight space limits while collecting light from varying field angles to monitor spectral composition or incoming light intensity. Shared challenges such as spot size, field angle, and light uniformity are addressed through lens selection, aperture adjustments, and ongoing simulation and design adjustments, balancing performance with practical design constraints.

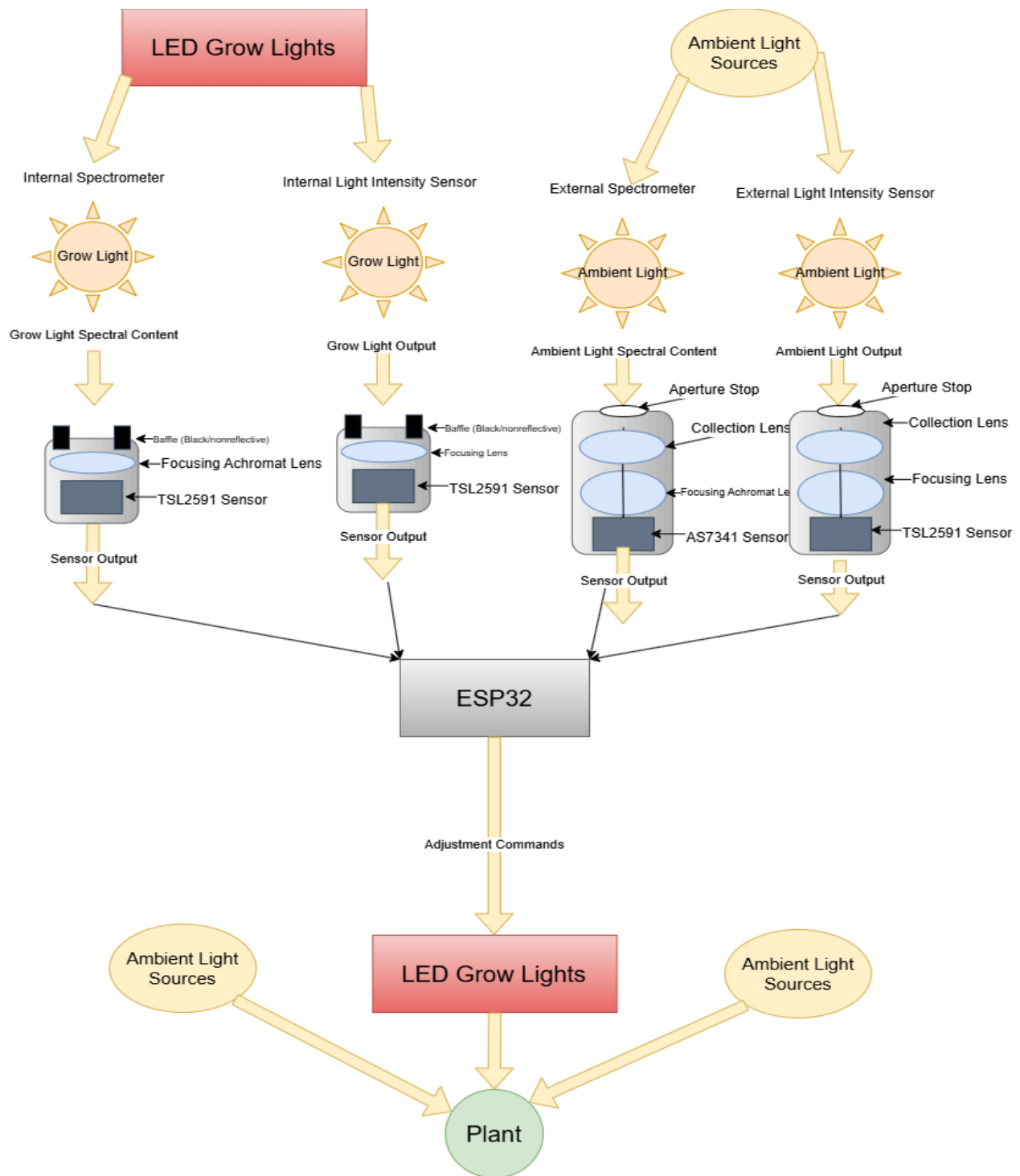


Figure 41: Diagram displaying the flow of light and information through the system's optical components.

6.10.1 Internal Spectrometer and Light Intensity Subsystems

The internal spectrometer system was designed as a compact, non-imaging optical assembly aimed at collecting light from the grow light source and focusing it onto the AS7341 spectral sensor. The primary objective of this subsystem is to measure the relative intensity of red (620–630 nm) and blue (465–475 nm) light emitted by the grow light, enabling precise control over spectral output based on real-time measurements.

The system does not employ diffraction gratings or spectral filtering elements, relying instead on the spectral channels of the AS7341 sensor. The optical design consists of a single achromatic doublet lens with a focal length of approximately 75 mm, selected to maintain a maximum system length of 3 inches, while ensuring the light is focused onto a spot size no larger than 5 mm in diameter. And because the sensor will be 6 inches from the grow lights, and pointed directly at them, we only need to ensure that the light collected will be within the 0–2° field of view. While spot size is a significant design constraint, maintaining wavefront uniformity across the sensor area is equally important in non-imaging systems to ensure consistent spectral measurements. The combination of low field angles, precise lens alignment, and the use of baffles helps preserve the purity of the collected light, ensuring light is only being measured from the grow lights, and minimizing variations that could affect the accuracy of red-to-blue light ratio detection.

To determine the appropriate focal length, the relationship between spot size D , focal length f , and the angular field θ was applied using the basic geometric optics formula:

$$D = 2f\theta$$

For a maximum spot size $D=5$ mm and maximum field angle $\theta=2^\circ$ (converted to radians as $\theta=0.0349$ rad), the required focal length is approximately:

$$f = \frac{D}{2\theta} = \frac{5}{2 \times 0.0349} \approx 71.6 \text{ mm}$$

A focal length of 75 mm was chosen to satisfy both the spot size constraint and the system length limit. This ensures efficient light collection within a 3-inch total system length, keeping the sensor illumination within design bounds.

Chromatic aberration is a key concern given the sensor's focus on red and blue light ratio measurement. The separation between wavelengths was minimized by selecting an achromatic lens. Such lenses are specifically designed to bring two wavelengths (typically in the blue and red regions) to the same focal point, reducing color fringing and focus errors across the operating spectral range. To achieve our desired parameters, the Thorlabs AC127-075-A achromatic doublet lens was selected as the primary focusing element for the internal spectrometer system. This lens offers a focal length of 75 mm and a diameter of 12.7 mm (0.5 inch), aligning with the system's maximum length of 3 inches and aperture size constraints. The AC127-075-A is optimized for the visible spectrum with an anti-reflection (AR) coating, ensuring high

transmission and minimal losses across the target wavelength ranges of 465–475 nm (blue) and 620–630 nm (red)

Aberrations such as spherical aberration and field curvature are negligible in this configuration due to low field angles ($0\text{--}2^\circ$) and the simplicity of the single-lens design. A baffle was incorporated to shield the optical path from stray ambient light, particularly at angles greater than 2° , ensuring consistency and reliability in spectral data collection.

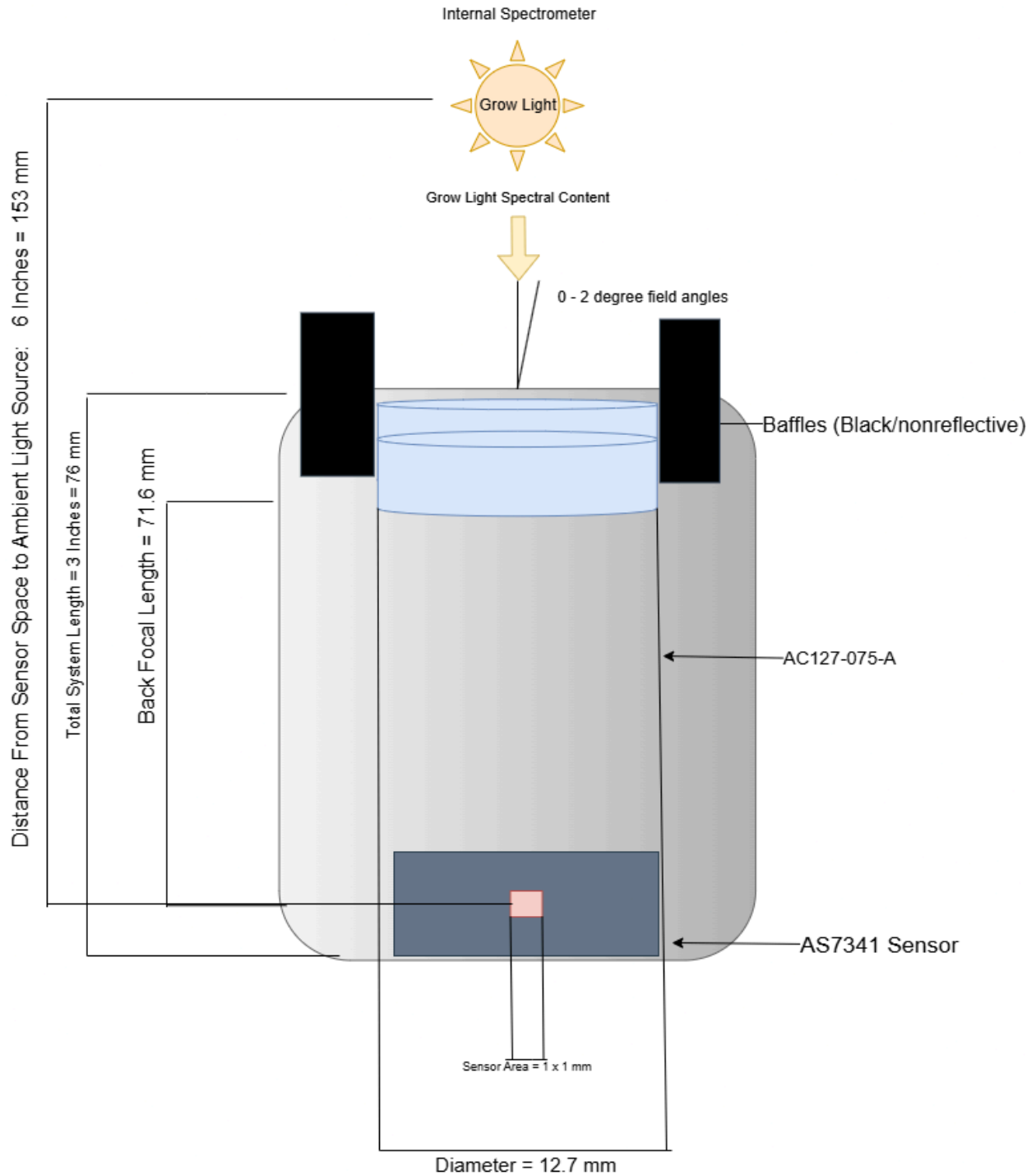


Figure 41: Diagram displaying the design and specs of the internal spectrometer system

The internal light intensity sensor subsystem is designed to monitor the illuminance the plant would be experiencing from the grow light LED array output. As the LEDs cannot inform the system as to their exact output, particularly not in units we can use, this data

would provide real-time feedback for controlling overall light levels, ensuring the plant receives light within the acceptable threshold defined at the time. The system is another non-imaging, light collection system, collecting light within a defined field of view and focusing it onto the TSL2591 sensor area, enabling accurate intensity measurements at high and low output levels.

Due to the similarities in sensor size and optical objectives, this subsystem shares much of its design appearance with the internal spectrometer system. However, significant differences in priorities result in important design modifications. Unlike the spectrometer, which requires precise chromatic aberration correction to measure distinct red and blue spectral bands, the light intensity sensor is only concerned with total visible light. Therefore, chromatic aberration is not a concern, allowing for a simplified and more cost-effective optical design.

The system uses a single plano-convex singlet lens to focus incoming grow light output onto the TSL2591 sensor space. Given cost constraints and the lack of spectral discrimination requirements, an achromatic doublet was deemed not necessary. Instead, a Thorlabs LA1213-A lens, with a focal length of 50 mm and diameter of 12.7 mm, was selected for its compatibility with the system's size and optical needs. This lens provides an efficient and cost-effective solution for light collection across the visible spectrum, ensuring accurate intensity measurement.

The lens focal length must satisfy the system's maximum length constraint of 3 inches (76 mm) while achieving a desired spot size of approximately 5 - 10 mm on the sensor plane. The relationship between focal length f , spot size D , and field angle θ is given by:

$$D = 2f\theta$$

Solving for the required field angle with a 50 mm focal length and 5 mm spot size:

$$\theta = \frac{D}{2f} = \frac{5}{100} = 0.05 \text{ rad} \approx 2.86^\circ$$

This calculation shows that a slightly wider field angle of about 2.9° is required, compared to the 2° used in the internal spectrometer. This increase is acceptable, especially given the TSL2591's wide dynamic range, and allows the system to remain compact while effectively focusing light onto the sensor.

Like the spectrometer system, the internal light intensity sensor shares the goal of preserving wavefront uniformity across the sensor area, as consistent illumination is crucial for reliable intensity readings. The use of low field angles and careful optical alignment ensures that both systems meet this non-imaging design requirement.

While chromatic aberration is not addressed in this design, spherical aberration remains a potential concern, particularly for light at wider angles. This is mitigated by proper lens orientation, with the plano side facing the sensor, and by limiting the maximum field angle to $\sim 3^\circ$. Additionally, a baffle is incorporated into the system to prevent stray light

from affecting the sensor, maintaining measurement accuracy under controlled grow light conditions.

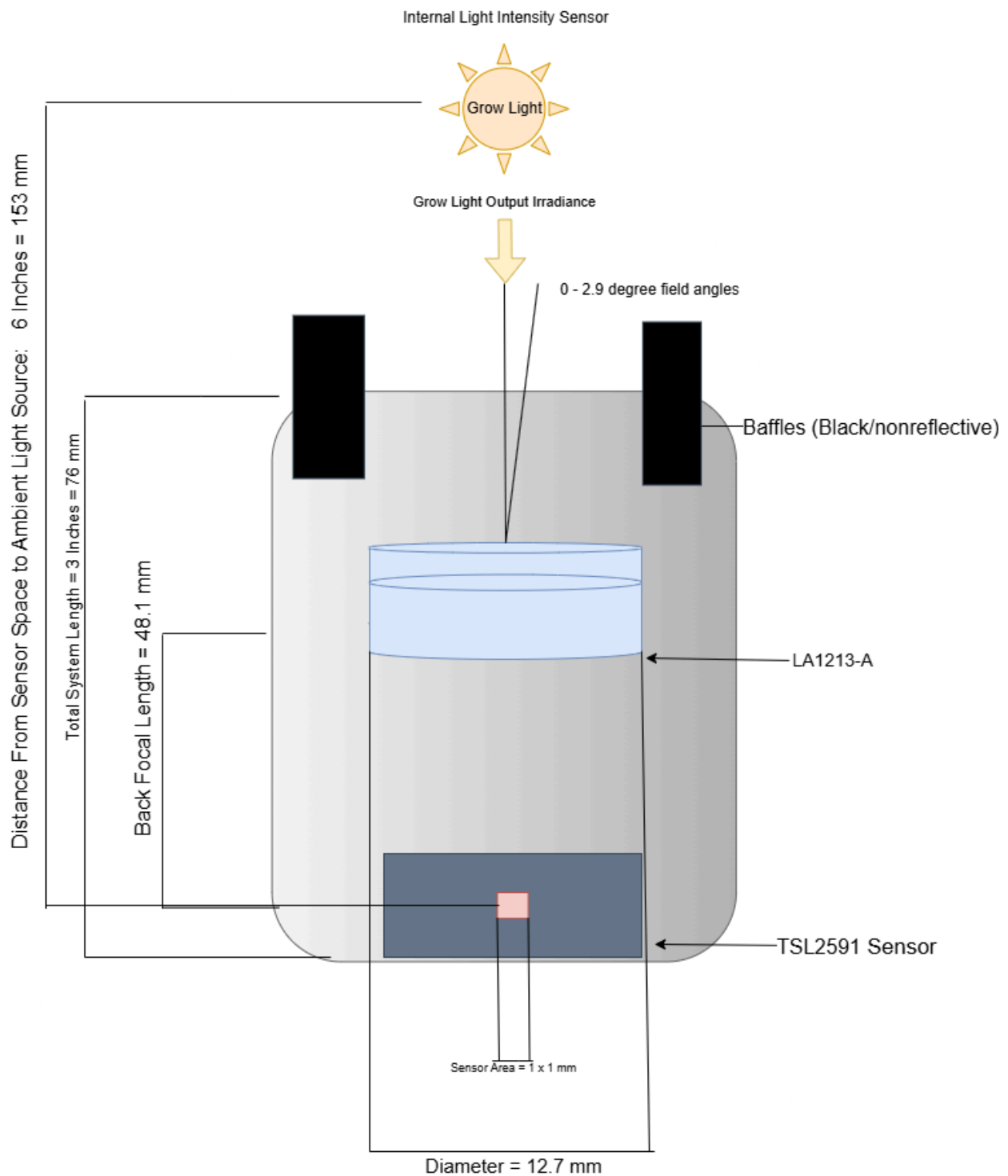


Figure 42: Diagram displaying the design and specs of the internal light intensity system

6.10.2 External Spectrometer and Light Intensity Subsystems

The external optical systems of the Bio-Sense Pot are designed to capture and analyze ambient light, allowing the dynamic lighting system to adjust its output based on real-world lighting conditions. These systems share several integral design objectives, including capturing light from a wide field of view, fitting within as small a physical space as possible, and the preference for using optical elements no larger than one inch in diameter, to avoid bulky housing that will block incoming light onto the plant. Both systems must also balance the desire for compact spot sizes with the reality of wide-angle light collection and system miniaturization.

Each external system, comprising the external spectrometer and the external light intensity sensor, uses similar optical layouts, involving a collection lens and a focusing lens that direct ambient light onto their active sensor area. These systems are ideally constrained to a maximum length of 5–6 inches, as to not block incoming light onto the plant, and must accommodate the necessary optical elements while ensuring integration into the Bio-Sense Pot structure. The 15° field angle is another shared design priority, as both systems must capture light from a broad area to produce reliable data reflective of the light environment experienced by the plant.

Given these shared parameters, general calculations apply across both systems. For a focal length of 15 mm and a field angle of 15° (0.2618 rad), the resulting spot size is:

$$D = 2 \times 15 \times 0.2618 \approx 7.85 \text{ mm}$$

This spot size, is not ideal, we don't want to vignette field angles off of the sensor space as this would violate the whole reason the design prioritizes 15°, given that both systems prioritize wide-angle light collection. Attempts to reduce the spot size, for example, by shortening the focal length to 10 mm, would reduce the spot to approximately 5.2 mm, but introduce significant financial and feasibility challenges in component sourcing and system integration. As a result, both systems are currently designed to operate with spot sizes in the range of 5–8 mm, possibly accepting this as a necessary trade-off for achieving broader light collection. Beyond these considerations, aperture stop size and placement are being explored in simulation to refine how both systems manage incoming light across the 15° field. By adjusting these variables, we hope to improve wavefront uniformity and light convergence, ensuring that despite the larger spot size, the light distribution on the sensor remains consistent and representative of the plant's ambient environment.

Despite these shared characteristics, the two systems differ in their specific functions. Unlike its internal counterpart, the external spectrometer focuses on measuring the average ambient spectral composition, allowing the Bio-Sense Pot to adjust the color balance of its grow light output to achieve an accurate red to blue ratio, as well as take some stress off of the system by possibly reducing output and letting ambient light carry some of the weight. It also uses the AS7341 spectral sensor, which benefits from capturing a broad range of light angles to provide a more comprehensive spectral profile.

Meanwhile, the external light intensity sensor is concerned with measuring the average ambient illuminance the plant is exposed to, particularly under low-light conditions. This system must be sensitive enough to detect subtle changes in ambient light levels, ensuring that the grow light compensates appropriately when natural light is insufficient.

Ultimately, both systems face similar design challenges and are being refined through ongoing simulation and component testing. The priority on wide field angles, compact form factor, and maximum light collection shapes every aspect of their design, while their individual roles in monitoring spectral data versus total light intensity guide the specific performance criteria that each must satisfy.

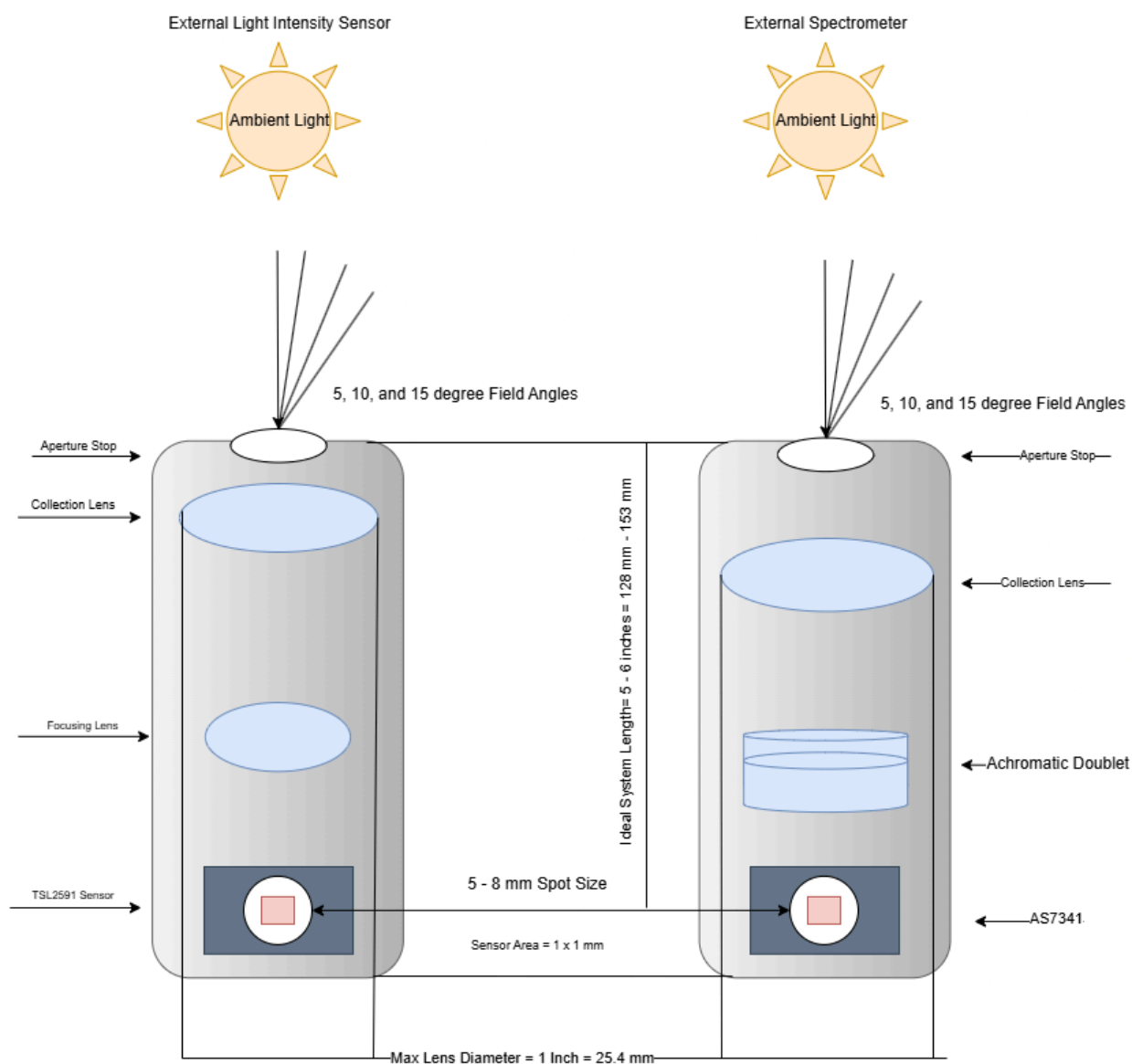


Figure 43: Diagram displaying the ideal conditions and design constraints of the external light collection systems

Chapter 7: Software Design

The software tools used in the BioSense project played a critical role in both the physical and electronic development of the system. For 3D modeling, we utilized TinkerCAD to design the custom structure of the pot and upper support, taking advantage of its user-friendly interface to create accurate models suitable for printing. FlashPrint5 was used to prepare these models for 3D printing, offering precise control over print settings and compatibility with our printer. On the electronics side, we used EasyEDA to design the schematic, select components, and create the PCB layout. Its integration with LCSC for part sourcing and its straightforward PCB design tools made it ideal for rapid prototyping. In addition to hardware design, we developed detailed software diagrams including flowcharts, case diagrams, state diagrams, and class diagrams to map the control logic, user interactions, and system behavior. The user interface was designed to work seamlessly with the onboard LCD screen, and we structured our data handling around efficient data transfer between components and optimized data structures for managing sensor input and system output. Together, these tools and diagrams helped streamline the transition from digital concept to a fully integrated smart plant system.

7.1 3D Modeling and Printing Workflow

To create the structural design of the BioSense system, we used TinkerCAD, a web-based 3D modeling tool that offered a simple and intuitive user interface. The platform allowed us to quickly design the three-part modular pot system, including the soil chamber, water reservoir, and electronics bay, along with the upper support frame. One key advantage of TinkerCAD was its ability to export STL files directly for 3D printing, which helped us move smoothly from concept to physical prototype without dealing with complicated CAD tools [58].

For the slicing and printing process, we worked with FlashPrint 5, the companion software for our FlashForge 3D printer. The software allowed us to control print quality settings, infill density, support generation, and temperature profiles depending on the part being printed. For structural components like the base and reservoir housing, we increased infill percentage to enhance strength, while more cosmetic parts were printed with lower infill to save material and reduce print time. FlashPrint 5 provided a good balance between beginner-friendly tools and advanced tuning options that supported the level of precision needed for our functional prototypes [59].

We also explored design-sharing platforms like Printables and MakerWorld for ideas and best practices from the 3D printing community. These platforms provided access to open-source models, some of which showed smart features like drainage channels, venting grids, and snap-fit locking systems. While we built our models from scratch, reviewing community designs gave us insight into how to improve usability and printability for indoor environments. It also helped us benchmark our own structural layout decisions by comparing similar enclosure concepts from other makers [60][61].

7.2 Schematic and PCB Layout with EasyEDA

For the electronic design of the BioSense system, we used EasyEDA, an online electronics design platform that let us create schematics, lay out PCBs, and select parts from a real-time parts library. Compared to more advanced tools like Altium or KiCad, EasyEDA was much easier to learn and navigate, especially for quick prototyping and education-based projects. The drag-and-drop interface for schematic design allowed us to link all sensors, regulators, and control modules without manually managing netlists. We also used its built-in library manager to select actual components available for order, which helped ensure that every part we used was both compatible and in stock [62].

One major advantage of EasyEDA was its direct integration with LCSC, a parts distributor. This made the BOM (Bill of Materials) generation and ordering process much more streamlined. Once the schematic was complete, we could switch to PCB mode and arrange components manually, adjusting trace widths, clearances, and grounding based on our power and safety constraints. The real-time design rule checker helped us stay within manufacturing tolerances, and we exported Gerber files directly from the platform for fabrication. For a project like BioSense, where we had both digital logic and higher-current devices like pumps and LEDs, having that full workflow in one tool saved a lot of time [63].

7.3 Software System Overview

The Bio-Sense Pot is made up of two main software components: the embedded firmware running on an ESP32 microcontroller and a web application that serves as the main way users interact with the system. These two components work together to create an automated and responsive environment for the plant while giving the user a way to monitor and control it remotely. The goal is to make plant care easier by combining real-time sensor monitoring, automated environmental adjustments, and a user-friendly interface. The ESP32 is responsible for handling all environmental monitoring and automation. It continuously reads in data from various sensors, including a soil moisture sensor, temperature and humidity sensor, light sensors, and two spectrometers. Based on this data, it makes decisions about whether to turn on the water pump, adjust the brightness or color ratio of the grow light, or send alerts to the user if something is outside of the ideal range. It also manages all communication between the pot and the web app, sending sensor data wirelessly and receiving any user updates or configuration settings.

The web app is being developed to give users access to their plant's information from any device with internet access. It allows users to create an account, identify their plant by either entering the species manually or uploading a photo, and view real-time sensor data such as temperature, humidity, light intensity, and soil moisture. In addition to displaying data, the app includes an AI-based chatbot that helps users understand what their plant needs, answer questions, and give care suggestions. The idea is to let the system handle most of the work while still giving users insight and control when they need it. The ESP32 and the web app stay in constant communication so that users

always have the most up-to-date information and the pot can respond to their commands in real time.

The entire software system is built using a modular and event-driven design. Each major function—like lighting, watering, or sensor reading—is handled by its own section of code, which keeps the system organized and easier to debug or expand in the future. The event-driven design means that actions are only triggered when they're actually needed, instead of looping or running constantly. For example, if the soil moisture drops below a certain threshold, the system triggers the pump to activate. If the light level changes, the grow light can automatically adjust its spectrum or intensity to compensate. This setup keeps the system efficient, scalable, and able to adapt quickly to changes in the environment.

7.4 Embedded Software Architecture

The embedded software running on the ESP32 is responsible for monitoring the environment, making decisions based on that data, and controlling the systems that adjust the plant's conditions. All of the code is written in Arduino C++ using the Arduino IDE, which provides a familiar and accessible environment for programming the microcontroller. The ESP32 was chosen not only because of its dual-core processing and built-in wireless communication capabilities, but also because it supports a wide range of sensors and communication protocols. While the current firmware operates on a single-threaded loop-based structure, the code is written in a way that can be upgraded to a multitasking architecture using FreeRTOS in the future to better utilize the ESP32's dual-core capabilities.

Right now, the main loop handles sensor readings, decision-making, and actuator control in a linear polling system. Each sensor is read on a cycle, and the values are stored in variables that are then checked against predefined thresholds. For example, if the soil moisture drops below a certain level, the pump is activated to water the plant. If the temperature or light values go out of range, the system reacts by adjusting the LED lighting accordingly. While this polling method is simple and effective for now, it's not the most efficient as the system grows more complex. In future iterations, interrupt-based readings will be introduced for sensors that support them, especially for faster reaction times and better power optimization.

The ESP32 communicates with the web application using a combination of HTTP and WebSockets. HTTP is used for sending configuration changes and other requests from the web app to the ESP32, while WebSockets are used to push real-time sensor data updates to the app. This setup allows for near-instantaneous communication between the pot and the user interface, which is critical for keeping the user informed and the system responsive. Although low-power or deep sleep modes are not currently implemented, they are part of the long-term plan to improve energy efficiency, especially for future versions that may rely more heavily on battery or solar power.

7.5 Sensor Integration and Data Processing

The Bio-Sense Pot relies on a network of sensors to gather real-time data about the plant's environment. Each sensor plays a critical role in helping the system make decisions about watering, lighting, and system feedback. All of the sensor data is read and processed by the ESP32, which then uses that information to either trigger a physical action (like turning on the pump or adjusting the lights) or send the data to the web application for the user to review.

The soil moisture sensor used in the system is a corrosion-resistant analog/digital hybrid probe from Istation. Right now, the ESP32 reads the analog signal through one of its ADC pins, converts the value to a percentage, and checks it against a preset threshold. If the moisture level is too low, the system activates the 5V submersible pump through an IRLZ44N MOSFET. The DHT11 sensor is used to collect both temperature and humidity data. While it's not the most precise sensor on the market, it is simple to use, low power, and accurate enough for the system's needs. These readings are taken on a timed polling cycle and stored in variables for logic processing and reporting to the web app.

For light sensing, two different types of sensors are used. The TSL25911FN is a high-precision light intensity sensor that reads lux values and is used to measure the brightness level from both ambient and artificial sources. These readings help the system decide whether to adjust the intensity of the WS2812B grow lights. Alongside the TSL2591s, there are two AS7341 spectral sensors which allow the system to analyze the composition of light. These sensors give us access to multiple channels across the visible and near-infrared range, which helps fine-tune the red and blue ratios in the grow light spectrum depending on the plant's needs and the lighting conditions of the room.

Other sensors in the system include an HC-SR04 ultrasonic sensor that acts as a water level detector for the internal reservoir. It helps the ESP32 determine whether the tank is low or full by measuring the distance between the sensor and the surface of the water. This helps prevent dry runs of the pump and can also be used to trigger a notification through the web app when it's time to refill. All sensor values are stored as global variables and, in the current version of the system, are not filtered or averaged — though this is something that may be added in a future version to help smooth out noise and increase reliability.

The ESP32 uses a TCA9548A I2C multiplexer to manage communication with the large number of I2C devices in the system, particularly the light sensors and LCD screen. This allows the ESP32 to easily switch between devices on the same I2C bus without address conflicts. Sensor values are pushed to the web app using WebSockets, allowing the user to view live readings in real time. The way the data is handled now is simple but effective: values are polled in the main loop, processed or compared against conditions, and either acted on or transmitted as-is. Later versions of the firmware may introduce object-based data structuring and in-place averaging to help clean up noisy data or make the logic easier to scale.

7.6 Lighting and Watering Control Logic

Lighting and watering are the two most important automated functions in the Bio-Sense Pot system. Both systems are directly controlled by the ESP32, and the logic for triggering each one is based on real-time sensor data. The goal is to make sure that the plant is getting enough water and the correct type and amount of light, all without needing manual intervention from the user.

The watering system works using a 5V submersible pump connected to a MOSFET (IRLZ44N) that acts as a digital switch. The ESP32 reads the soil moisture value from the Icestation analog sensor and checks if it falls below a set threshold. If the moisture level is too low, the ESP32 activates the pump for a preset duration to deliver water to the soil. After watering, the system pauses for a short time to let the moisture settle before taking another reading. This prevents the pump from being turned on too frequently or running unnecessarily. The water pump logic is simple but effective for this version of the system, and in future versions, the timing and thresholds could be adjusted dynamically based on plant type, growth stage, or historical moisture patterns.

The lighting system uses WS2812B individually addressable RGB LEDs to create a fully customizable grow light setup. The ESP32 adjusts both the brightness and the red/blue color ratio of the LEDs based on data from two types of sensors. The TSL25911FN sensors measure the overall light intensity in the environment, while the AS7341 spectral sensors provide more detailed readings of the actual light composition. If the environment is too dim, or if certain wavelengths like red or blue are lacking, the ESP32 will automatically increase the output of those specific channels on the grow light to compensate. This helps maintain optimal Photosynthetically Active Radiation (PAR) exposure and ensures consistent growth conditions, especially when ambient light is unstable or insufficient.

Both systems are event-driven and operate only when needed. This not only helps conserve power, especially when the system is running on battery or solar input, but it also reduces unnecessary stress on the components and avoids overwatering or excessive light exposure. All thresholds and light settings are currently hardcoded for testing purposes, but future versions of the firmware will allow these values to be customized based on plant type through the web app. The long-term goal is to make the lighting and watering systems fully adaptive, adjusting in real-time using feedback from the sensors, the user, and even AI-based predictions on plant needs.

7.7 App Software Design

The web application is intended to be the primary way users interact with the Bio-Sense Pot system. It will give users access to real-time environmental data, plant identification tools, and system controls, all from a clean and easy-to-use interface. The overall structure of the app is planned with modularity in mind, so that new features can be added or changed without affecting the rest of the system. Responsiveness and ease of

access across different devices will also be a major focus, since the app is expected to be used on both desktop and mobile browsers.

The user interface will begin with account creation and login, giving users the ability to save plant settings and preferences for personalized automation. After logging in, the dashboard will serve as the central hub for displaying live sensor data such as temperature, humidity, moisture levels, light intensity, and water level. These values are expected to update in real time using WebSockets, allowing users to monitor their plant's condition without needing to refresh the page. The plant identification feature will include both manual selection and photo upload options, helping the system tailor its watering and lighting logic based on the plant species.

Another feature planned for the app is an AI-based chatbot assistant that will help answer questions and give care recommendations based on current sensor readings. The assistant will be used to make the experience more interactive and helpful, especially for users who are new to plant care. Adjustments to system settings—such as moisture thresholds or lighting preferences—will be handled through HTTP requests sent from the app to the ESP32. Data exchanged between the web app and the pot will be structured using JSON, keeping the process lightweight and easy to work with. Future updates may also include visual graphs for sensor data over time, giving users more insight into their plant's health trends and environmental changes.

7.8 Communication Between Pot and App

Communication between the Bio-Sense Pot and the web app is planned to be handled through a combination of HTTP and WebSocket protocols. This dual-approach allows for efficient, real-time interaction while also maintaining flexibility for on-demand updates or system changes. The ESP32 will act as the communication bridge, pushing sensor data to the cloud and receiving commands or settings from the user via the app.

WebSockets are intended to handle real-time data transmission from the ESP32 to the web app. This makes it possible for users to view up-to-date sensor values without needing to refresh or manually request the information. Each time the ESP32 takes a new reading—for example, from the soil moisture or temperature sensors—it will package the data in a structured JSON format and send it over a persistent WebSocket connection to the server or directly to the app, depending on the architecture used.

HTTP requests will be used for user-initiated actions, such as changing lighting settings, triggering a manual watering cycle, or updating the plant profile. These commands will be sent from the app to the server and then forwarded to the ESP32. The ESP32 will parse the request and make the appropriate system-level changes. Responses from the ESP32 can be returned via the same HTTP channel or confirmed over WebSocket to ensure that changes are successfully applied. This separation of duties allows WebSockets to handle fast, frequent data updates, while HTTP takes care of slower, less frequent commands that require confirmation.

This approach is being designed to keep the system efficient and responsive, while also being scalable as more features—like user-defined thresholds or growth tracking—are added. Although the current communication system is still in development, the planned structure provides the flexibility needed to support both autonomous system behavior and direct user interaction through the web app.

7.9 UI and UX Design

The user interface for the Bio-Sense Pot web app is being designed to be as simple and intuitive as possible. Since the target users may not have technical backgrounds, the main focus is on clarity and ease of use. The layout will follow a clean, card-style structure, with all of the most important information—like current temperature, humidity, soil moisture, and light levels—displayed up front on the main dashboard. Visual indicators like progress bars, icons, and color-coded alerts will be used to help users understand the plant's condition at a glance.

Navigation within the app is being planned around a straightforward structure, with a sidebar or top menu giving access to pages like the Dashboard, Plant Identification, Settings, and Chatbot Assistant. The dashboard will serve as the main hub, showing all live data and allowing for quick access to system status and manual control functions. The plant identification page will offer both a dropdown menu for manual selection and an image upload option for automated recognition. Once the plant is selected, the app will suggest ideal lighting and watering parameters tailored to that species.

The chatbot will be integrated into its own page or sidebar widget, allowing users to ask questions or get suggestions without leaving the current screen. The overall color scheme and layout are being designed with readability in mind, using neutral backgrounds and contrasting text to ensure everything is easy to read on both desktop and mobile browsers. The interface will also include pop-up alerts or notification banners to inform users when critical events occur, like low water levels or out-of-range temperature readings. As development continues, user feedback and accessibility considerations will be taken into account to refine the design and improve the overall experience.

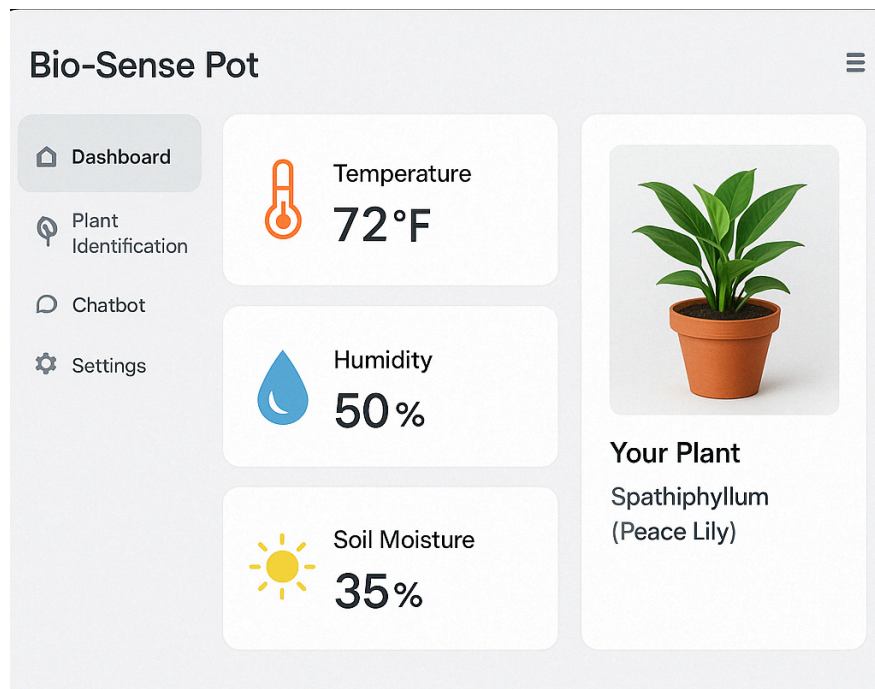


Figure: UI Mockup Example

7.10 Security and Data Privacy

Security and data privacy are important considerations in the design of the Bio-Sense Pot system, especially since users will be accessing the platform remotely and interacting with sensor data over the internet. While the project is still in development, steps are being planned to ensure that the system can store and transmit information securely without compromising the user's privacy or exposing the system to vulnerabilities.

User authentication will be handled through a secure login system, with plans to use email and password credentials stored in a protected backend. Data exchanged between the web app and the ESP32 will be transmitted using standard protocols like HTTPS and WebSocket over TLS, both of which help protect the integrity and confidentiality of the data. This means sensor data, user inputs, and system updates will be encrypted during transmission, reducing the risk of interception or manipulation.

On the backend side, user data such as plant profiles, sensor preferences, and system settings will be stored securely, with access restricted to authenticated users only. The system is being designed with minimal data storage in mind to reduce risk—no sensitive personal information beyond basic login credentials and optional plant configuration will be collected. In future versions, additional layers of security may be added such as rate limiting, input validation, and multi-factor authentication, especially if features like remote control or cloud logging are expanded. While the platform will remain focused on usability, maintaining user trust and protecting system integrity will be treated as a priority throughout development.

For all software flowcharts refer to section: 2.5.2 Flow Charts

Chapter 9: System Testing and Evaluation

The *System Testing and Evaluation* phase verifies the Bio-Sense Pot's key subsystems, including lighting, watering, and power. The WS2812B LED grow light and calibrated light sensors were tested for sufficient output, and will be further tested when physically implemented into an LED array. Diffuser candidates and spectrometers were evaluated to ensure light uniformity and spectral accuracy. The automatic watering system, using a D-FLIFE soil moisture sensor and IRLZ44N MOSFET, reliably triggered the 5V pump based on moisture thresholds. An ultrasonic sensor monitored water levels and enabled refill alerts. A 5V relay was replaced with a MOSFET to eliminate interference issues. The initial 3.7V battery setup was upgraded to two 8.4V power sources with LM2596 converters, supporting higher current loads for LEDs and the pump. Charging and protection were managed using a TP5100 module and 2S BMS, ensuring stable operation and extended runtime.

9.1 Optoelectronics and Optical Systems Feasibility Study and Testing

The Bio-Sense Pot's optoelectronics systems, including the WS2812B LED grow light, light sensors (TSL2591, VEML7700 and AS7341), types of diffusers, and spectrometers, have undergone a comprehensive pre-integration testing and validation process to ensure functional integration, performance consistency, and system cohesion feasibility, both physically and electrically. The tests have focused on validating sensor response accuracy, developing calibration curves, and confirming the feasibility of key light collection and measurement tasks using The LED grow light has been evaluated for light output adequacy, thermal behavior, current impact, and effectiveness in meeting plant saturation thresholds, with measurements taken using our light sensors, and pre-calibrated ones. Light sensors have undergone pre-integration testing and preliminary calibrations to ensure adequate functionality, and prepare for full experimental calibration under final system conditions. A selection of diffusers have been assessed for light dispersion, size, weight, and transmission. The AS7341 spectrometers have undergone functionality testing and preliminary spectral accuracy testing to allow for equivalent readings with a calibrated spectrometer. The LCD dome remains a conceptual feature, with feasibility exploration focused on functionality, physical manipulation viability, and optical clarity. Together, these tests aim to validate the system's ability to deliver consistent, responsive, and energy-efficient dynamic lighting performance, while identifying integration challenges and informing future iterations of the Bio-Sense Pot's optoelectronic subsystems.

9.1.1 LED Grow Light

The feasibility of the WS2812B LED strip was determined based on its ability to meet the Bio-Sense Pot's primary design requirements, both physical fit and optical performance within the Bio-Sense Pot's 6x6 inch grow area. Each strip contains 100 individually addressable RGB LEDs per 3.28 feet (1 meter), with a strip width of 10 mm, allowing it to be securely mounted on a flat surface above the plant zone without obstructing sensor visibility or airflow. A 13-inch section of the strip was used for testing, representing the expected length needed for full grow space coverage.

Color and intensity control were verified through independent testing of the red (633 nm), green (520 nm), and blue (465 nm) channels. Each LED operates at 5V DC, drawing approximately 60 mA per LED when all three color channels are active at full brightness, or ~18 mA per LED per color. The total power consumption for the tested 13-inch segment (~33 LEDs) is estimated at ~6.6W under full white output. Control signals were supplied via an ESP32 microcontroller, which managed brightness scaling and color channel selection with no latency or flicker observed across a full range of settings.

To simulate the system's final light dispersion, a clear acrylic diffuser (70–80% transmission) was placed 1 inch in front of the LEDs. Light output was measured at 3 inches and 9 inches from the diffuser using a calibrated power meter. Peak values reached 75.9 μW (red), 91.4 μW (green), and 139.6 μW (blue) at 3 inches from the diffuser, and 32 μW (red), 39.5 μW (green), and 59 μW (blue) at 9 inches from the diffuser. Intensity decreased with distance as expected from the inverse square law, with consistent readings confirming stable LED behavior across all test conditions. The light output scaled linearly with software-controlled intensity levels, supporting the planned dynamic lighting routines for adaptive plant growth. Though the output with this experimental setup is not astounding, it should be noted that this was a single line of LEDs, and not the 100 LED array, which would have substantially higher output.

Thermal behavior was within acceptable limits during short-term tests, with no significant heating noted at maximum intensity. The LED strip's construction and electrical characteristics align with the system's overall power budget, making it a suitable and efficient choice for continuous use in the controlled lighting cycles of the Bio-Sense Pot.

9.1.2 Light Sensors

The external light intensity sensor, initially planned as the VEML7700, was replaced with a second TSL2591 after early tests revealed significant inconsistencies. Despite adjustments to gain and integration time, the VEML7700 displayed drastic variations under identical lighting conditions, leading to concerns about its reliability in controlled calibration. The TSL2591, by contrast, demonstrated stable and repeatable results,

making it the preferred choice for both internal and external light monitoring within the Bio-Sense Pot.

External light intensity sensor testing was conducted within a controlled environment in a dark room to eliminate ambient light interference. The light source used was a Fiber-Lite High Intensity Illuminator, delivering consistent broadband white light across ten distinct intensity levels. Each light level was first measured with a calibrated power meter to establish a baseline, followed by TSL2591 sensor readings at identical distances of 3 inches and 9 inches from the light source. Both the power meter and sensor were positioned consistently to ensure identical exposure during each test.

To ensure accurate and repeatable results, a comprehensive validation process was conducted involving multiple sensors and meters. A total of six power meters and five light sensors were compared. The process began with identifying the power meter that provided results closest to the mean values of all devices tested. Meter 4 demonstrated the most consistent output and was provisionally selected for further comparison.

Following the initial power meter selection, each light sensor was tested under identical conditions using Meter 4 as a reference. Sensor 4 consistently produced stable readings in alignment with Meter 4, outperforming the other four sensors in both accuracy and repeatability. A final verification phase involved retesting all six power meters with Sensor 4 to confirm the integrity of Meter 4's results. The outcome reaffirmed Meter 4's selection, establishing Sensor 4 and Meter 4 as the reference devices for all subsequent external light calibration procedures.

The Newport 918D-SL-OD3R power sensor paired with the Newport 1919-R power meter formed the calibrated reference system. This system was capable of accurately capturing light intensity across the visible spectrum, making it suitable for calibrating the TSL2591's lux readings against actual irradiance.

With the calibrated reference devices established, the next phase of testing focused on capturing the necessary data to develop precise calibration curves for the external TSL2591 light sensor under controlled lighting conditions. Measurements were conducted in a dark room, using the Fiber-Lite High Intensity Illuminator, which provided a consistent broadband white light source that was adjustable across ten distinct intensity levels. For each level, the Newport 918D-SL-OD3R power sensor, configured for accurate visible light detection, recorded the optical power in microwatts, serving as the baseline for irradiance calculations. To fully characterize the sensor's response across the spectrum of PAR, the power meter was set to three specific wavelength compensation settings corresponding to the red (633 nm), green (520 nm), and blue (465 nm) light. For each of these settings, a series of ten power measurements were taken, covering the full intensity range. This process was performed at two distances from the diffuser, 3 inches and 9 inches, to simulate the expected possible variation in canopy height within the Bio-Sense Pot. In total, sixty power measurements were collected, ten per wavelength setting at each distance, ensuring that the sensor calibration process accounted for both spectral differences and distance-based falloff.

To correlate these reference values with the TSL2591's sensor output, an identical sequence of measurements was performed with the external TSL2591 positioned in the same positions as the power sensor. The sensor operated at a low gain setting ($\times 1$) with a 100-millisecond integration time, determined by testing the sensor's output at high and low intensity levels, and at the far and close distances, to ensure the sensor wouldn't over saturate or fail to get a reading. Sensor readings were recorded as lux values, derived from the device's internal process of subtracting channel 1 (IR light) from channel 0 (all light) so that we would only be measuring visible light. Readings were recorded with careful attention given to maintaining consistent orientation and distance for each light level. Each of the ten intensity levels was measured at both 3-inch and 9-inch distances, resulting in twenty TSL2591 readings directly corresponding to the power meter's dataset. These paired measurements provided the foundation for calculating irradiance and subsequently deriving a conversion curve that translates TSL2591 lux readings into PPFD ($\mu\text{mol}/\text{m}^2/\text{s}$), the standard unit for quantifying photosynthetically active radiation. The use of a 70–80% transmission diffuser between the light source and the sensors ensured even light distribution and a realistic simulation of the Bio-Sense Pot's finalized conditions, while the consistent setup across all tests preserved the integrity of the experimental calibration process.

To translate TSL2591 sensor readings into meaningful units of light intensity for plant growth, we developed a calibration process linking lux readings to photosynthetically active photon flux density (PPFD). The process began by converting power meter readings, taken in microwatts, into irradiance values in watts per square meter. This was done using the formula:

$$E = \frac{P}{A}$$

where P is the power measured by the Newport sensor, and A is the known sensor area. This step allowed us to determine how much light energy was falling on a given surface area at each tested intensity.

Next, irradiance values were converted into PPFD, which is a standard unit used to measure light useful for photosynthesis, expressed in micromoles of photons per square meter per second. This conversion used the relation:

$$PPFD = \frac{E}{E_{\lambda}}$$

where E_{λ} is a constant that depends on the wavelength of the light. For white light, an averaged factor of 0.219 was used based on typical spectral distribution. This allowed us to associate each power meter reading with a PPFD value, creating a reference to match against the sensor's lux output. After the lux and PPFD readings across all light levels, we used a fitted curve to describe their relationship. For the external light sensor, exposed to broadband white light, a second-order polynomial provided the most accurate fit. The curve equation was:

$$PPFD = -3.200762 \times 10^{-7} \cdot Lux^2 + 0.051459 \cdot Lux - 27.9655$$

This curve was derived from all tested levels and distances, capturing the sensor's response across its full operating range. As shown in the plotted conversion curve (Figure X), this equation closely followed the actual data, particularly at higher lux levels where some non-linearities appeared.

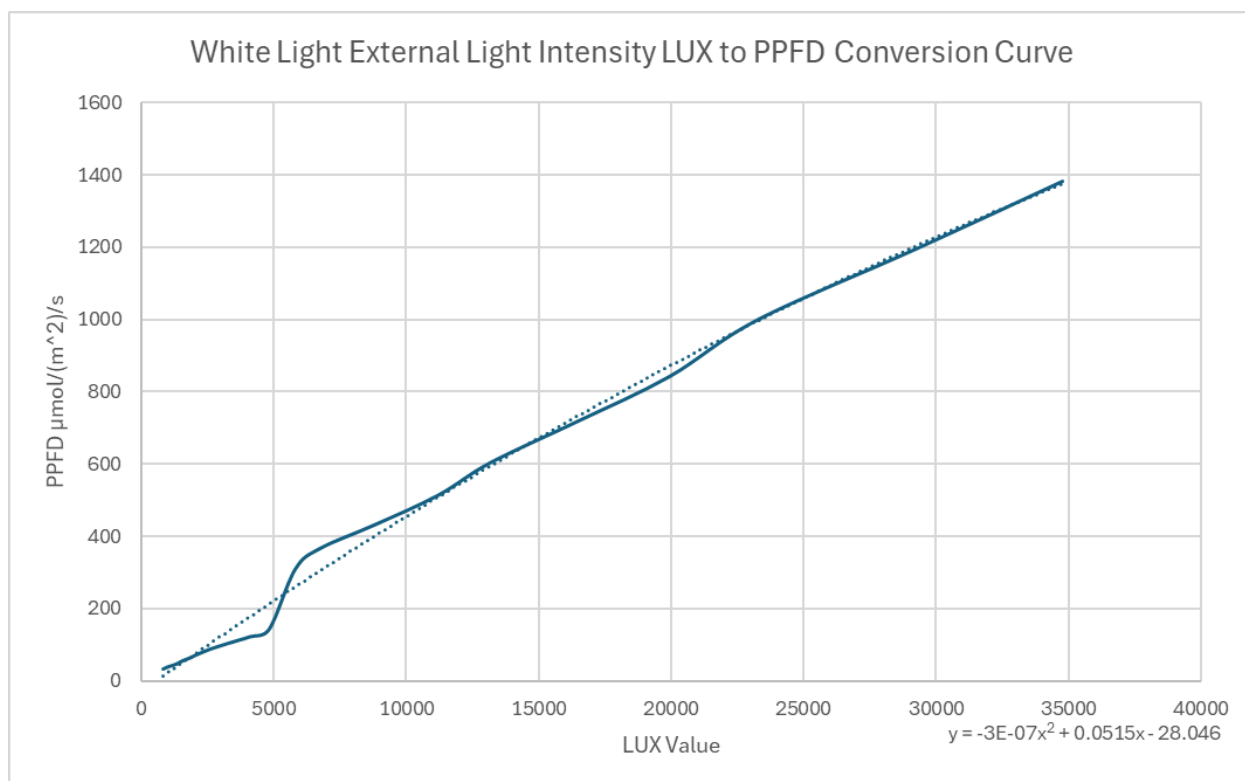


Figure 45: Graph displaying the PPFD conversion curve for white light for the external light intensity sensor

In practice, this equation is applied directly in the Bio-Sense Pot's firmware. Whenever the TSL2591 measures a lux value, that number is passed through this curve to calculate the current PPFD. This real-time PPFD value is used by the system to decide whether to adjust the grow light output, referring to the set thresholds of the plant at that time, ensuring plants receive optimal light while avoiding excess energy use. By embedding the curve into code, the sensor's lux readings can be automatically converted, allowing dynamic responses to changing ambient light conditions.

The internal light intensity sensor followed a similar testing process as the external sensor, but instead of a single white light source, measurements were taken using the WS2812B LED strip. The LED strip was configured to output red (633 nm), green (520 nm), and blue (465 nm) light individually, at ten distinct intensity levels for each color.

Light from the LED strip passed through a clear acrylic diffuser with a transmission of approximately 70–80%, helping to ensure even light distribution over the sensor surface. The diffuser was made from a solid acrylic sheet with a film, simulating the light conditions expected in the final Bio-Sense Pot system.

For each color, measurements were taken again at distances of 3 inches and 9 inches from the diffuser. At each level and distance, the Newport power meter recorded the true light intensity, while the internal TSL2591 sensor recorded corresponding lux values. These paired readings allowed us to generate individual calibration curves for red (Fig 46), green (Fig 47), and blue light (Fig 48). Each curve followed a linear relationship between the sensor's lux reading and the calculated PPFD for that specific color, with separate slope and intercept values derived through regression analysis. By calibrating each color channel independently, we can ensure that the sensor's natural tendency to overvalue green light (due to photopic lux weighting) is corrected, with each curve accounting for its respective spectral response.

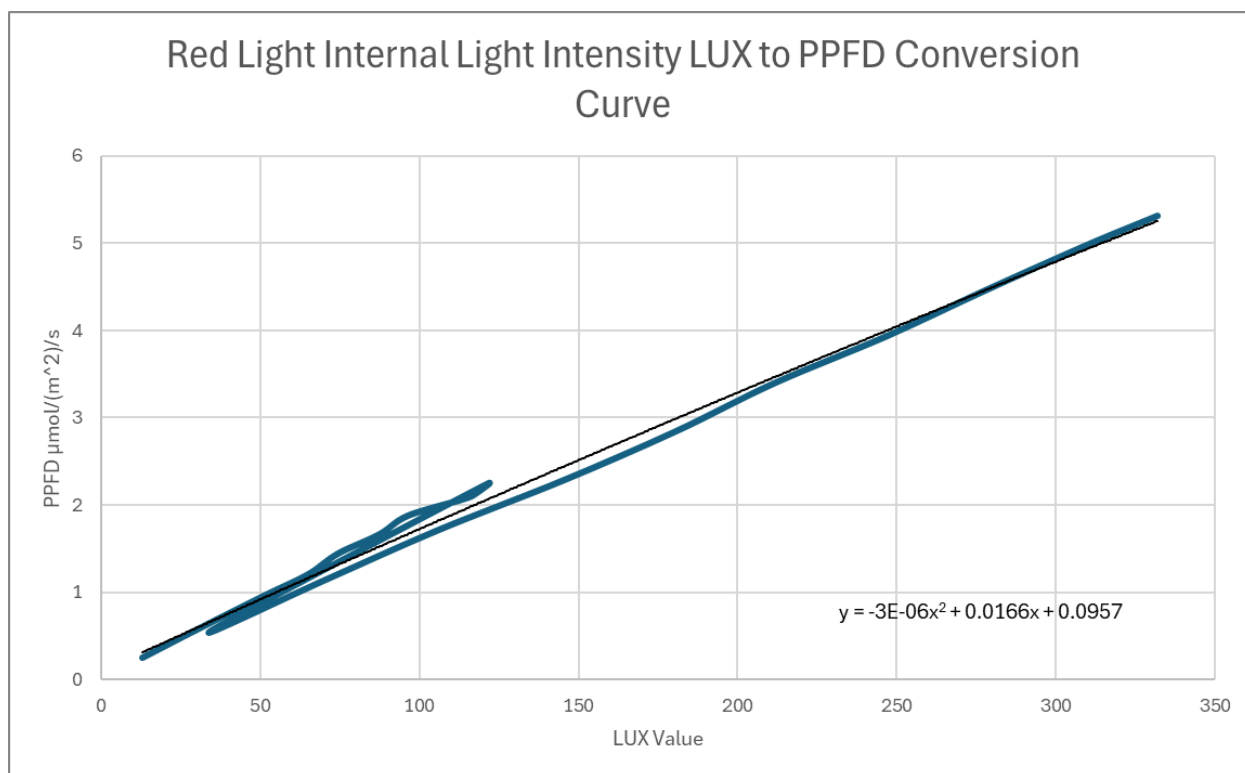


Figure 46: Graph displaying the PPFD conversion curve and equation for red light for the internal light intensity sensor

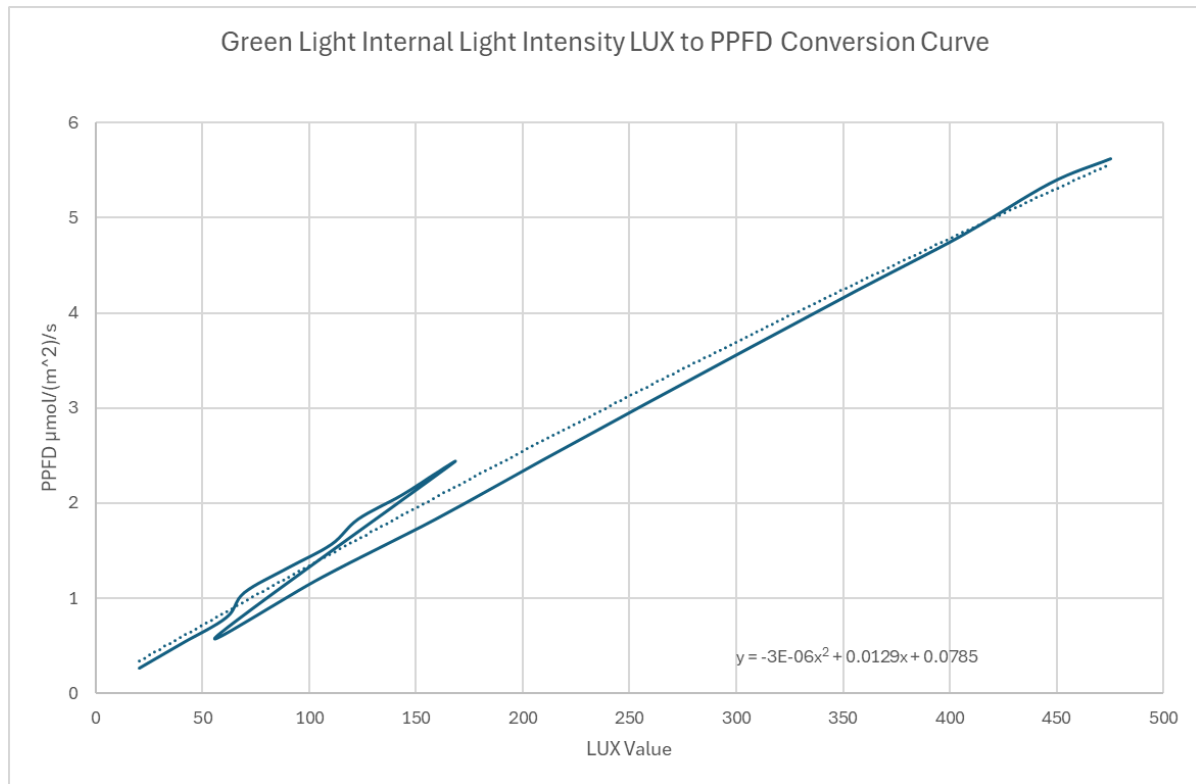


Figure 47: Graph displaying the PPFD conversion curve and equation for green light for the internal light intensity sensor

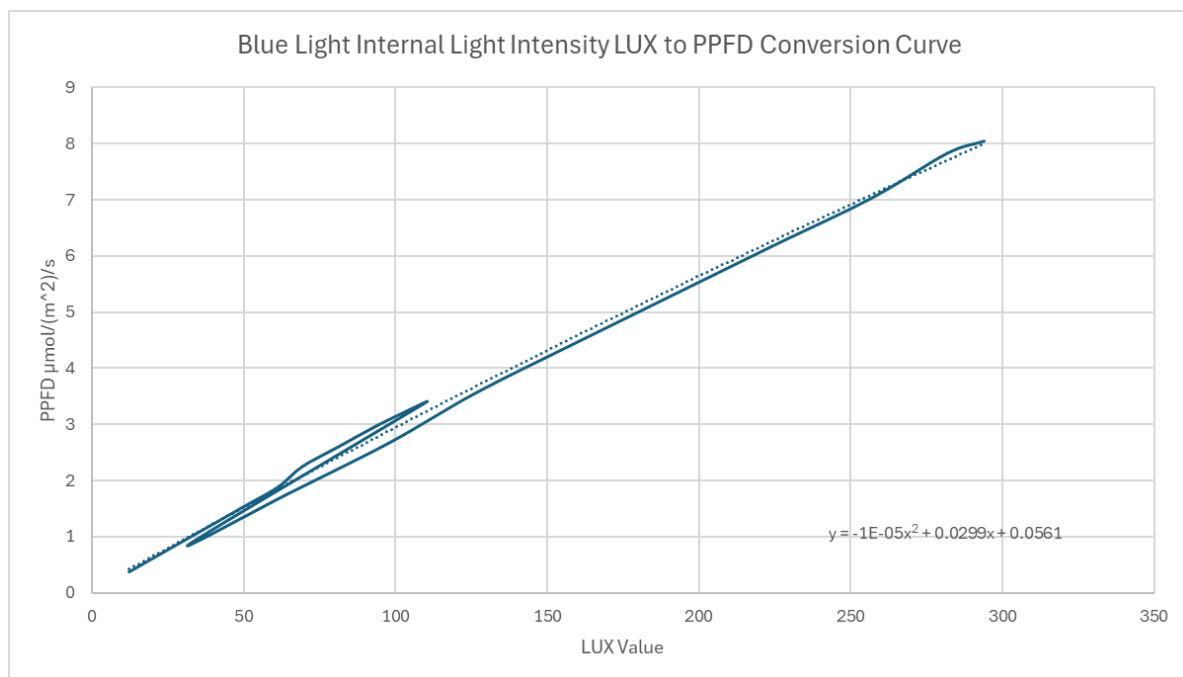


Figure 48: Graph displaying the PPFD conversion curve and equation for blue light for the internal light intensity sensor

These color-specific curves are used in the firmware to accurately convert lux readings into PPFD, depending on which LEDs are active. When only one color channel is used, the sensor reading is applied directly to that color's curve. For example, when red LEDs are on, the system applies the red curve to determine PPFD. When multiple colors are active, PPFD values from each curve are scaled based on the LED drive levels and summed, ensuring precise light measurement during dynamic multi-color lighting. This approach allows the internal sensor to provide accurate real-time feedback, supporting adaptive lighting control throughout various plant growth stages.

9.1.3 Light Diffusers

The selection of a suitable light diffuser for the grow lights was guided by a comparison of materials based on their optical and physical properties. Key requirements included effective light diffusion, high optical transmission (ideally between 70–90%), lightweight construction, and the ability to be easily cut and shaped to fit the grow light housing. These factors were essential to ensure even light distribution over the plant canopy without adding unnecessary weight or complexity to the grow light assembly.

Various diffuser materials were considered, including ground glass, opal acrylic, and flexible polymer films. Ground glass offered excellent diffusion but was too heavy and expensive. Thin polymer diffusers provided flexibility but lacked the structural rigidity needed for consistent positioning. The final selection was a clear acrylic diffuser with an intact protective film, which met all design and performance requirements. This material offered reliable light diffusion while maintaining a transmission range of approximately 70–80%, ensuring that sufficient light passed through to reach the plants effectively. The acrylic sheet was also lightweight and could be easily cut to fit the grow area, making it a practical and efficient choice for the Bio-Sense Pot's dynamic lighting system.

9.1.4 Spectrometers

To evaluate the accuracy and viability of the AS7341 spectrometer for use within the Bio-Sense Pot, comparative testing was done against a calibrated StellarNet, Inc. GreenWave16 VIS-25 spectrometer. The GreenWave16 spectrometer had previously been validated against multiple other Spectra-Wiz laboratory-grade spectrometers using a 633 nm He-Ne laser, where it demonstrated the most accurate reading, consistently reporting the closest centroid wavelength of approximately 633 nm. Based on this verification, the GreenWave16 spectrometer was used as the reference device for all spectrometer calibration procedures.

The testing process involved exposing both the GreenWave16 and the AS7341 spectrometer to the same light conditions, using the WS2812B LED strip as the light source. The LED strip was programmed to emit various blended colors, including violet, gold, orange, purple, and mint green, allowing for a broad spectral range to be

analyzed. For each color combination, both spectrometers recorded the intensity (in arbitrary units) at the two highest spectral peaks. The relative strength of these peaks was used to compute a ratio, which served as the basis for comparing the two sensors and establishing calibration.

Results indicated that while the GreenWave16 spectrometer provided stable and consistent ratios across all color tests, the AS7341 exhibited significant deviations, particularly overestimating the intensity of red light. In all cases, the AS7341's peak ratios diverged from those recorded by the calibrated spectrometer, sometimes to a factor of 5, suggesting that the sensor's internal channel scaling did not align with actual spectral distributions. Despite these discrepancies, the AS7341 spectrometer remains a viable component for the Bio-Sense Pot, with ongoing efforts focused on correcting its spectral response through software adjustments, and committing to further investigation into any experimental problems that may have occurred. Calibration corrections will be applied to re-balance the sensor's output, ensuring it can deliver accurate spectral measurements under real-world operating conditions.

9.1.5 LCD Dome

Due to the LCD dome's current status as a stretch goal, no formal physical testing has been conducted at this stage. However, preliminary feasibility examination has been explored through the analysis of material availability and pricing, as well as physical integration feasibility. The LCD Dome was envisioned as a dynamic shading system, designed to regulate ambient light entering the Bio-Sense Pot by using voltage-controlled LCD film that could transition between transparent and opaque states. This would have allowed the system to reduce excessive external light while maintaining internal lighting conditions optimal for plant growth.

Efforts to source appropriate LCD materials revealed significant problems. Suppliers offering LCD films or panels that were suitable for physical implementation generally required bulk purchases at costs well beyond the project's budget, with no reasonable options for single-unit or prototype-scale acquisition. In addition to pricing, the majority of available LCD materials were designed for flat or rigid surfaces like windows, posing challenges for wrapping or shaping the dome around the plant pot in the intended configuration. Given these limitations in both cost and physical adaptability, the LCD Dome is not expected to be integrated into the current system. While the concept remains a potential enhancement for future versions of the Bio-Sense Pot, it is likely not feasible within the scope and resources of this project.

9.2 Automatic Watering System Testing and Evaluation

The Bio-Sense Pot's automatic watering system was rigorously tested to validate the functionality and reliability of its core components: the D-FLIFE soil moisture sensor, 5V submersible water pump, IRLZ44N MOSFET, and HC-SR04 ultrasonic sensor. Central to the watering logic is the soil moisture sensor, which was connected to the ESP32's analog input on GPIO 34. During testing, this sensor consistently provided analog voltage readings corresponding to soil moisture levels, which were converted into percentage values. A moisture threshold (e.g., 35%) was established in firmware to determine when watering was necessary. When soil moisture dropped below this threshold, the ESP32 sent a digital HIGH signal to the MOSFET's gate to activate the pump. Extensive testing confirmed that the sensor could detect varying soil conditions from dry to saturated and trigger the pump appropriately. The readings were also monitored under different power supply conditions to verify stability. However, initial tests using a 5V relay module introduced electrical noise and voltage dips that interfered with analog readings, causing erratic behavior in the soil sensor and occasional failure in other components.

To resolve this issue, the 5V relay module was replaced with an IRLZ44N logic-level MOSFET. This transition significantly improved the system's reliability and signal integrity. The MOSFET allowed for smooth, low-power switching of the submersible pump without affecting analog readouts or introducing EMI (electromagnetic interference). Bench testing showed that the IRLZ44N could be fully turned on by the 3.3V logic output from the ESP32, ensuring robust control of the 5V pump without the need for additional driving circuitry. Load tests confirmed the MOSFET operated efficiently under continuous watering cycles, with minimal heat generation and no impact on the ESP32's performance or other sensors. This modification also reduced component bulk and power draw, making it more suitable for a battery-powered system.

The submersible 5V water pump was tested for flow rate, noise, and operational consistency. Connected to the MOSFET's drain pin and powered via a regulated 5V rail, the pump activated reliably whenever the soil moisture fell below the programmed threshold. Testing under different soil types and pot sizes validated that the pump provided adequate water delivery within seconds of activation. The system was tested both with and without a delay interval to control the total watering time. Flow uniformity and water pressure were sufficient for typical indoor plant setups. Long-duration tests were also conducted to assess whether repeated cycling impacted performance or induced mechanical wear, and no degradation was observed.

Additionally, the HC-SR04 ultrasonic sensor was integrated to monitor the water reservoir level. It was calibrated to measure distance from the sensor to the water surface, with the ESP32 converting this into a percentage value representing reservoir

fullness. Accuracy was validated using a ruler for known distances and comparing the sensor's output under varying tank heights. This data was displayed on the LCD and also sent to the user interface, alerting users when water levels fell below a refill threshold. Testing included detection consistency under high humidity conditions and noise rejection when nearby components were active. Overall, the ultrasonic sensor proved to be a cost-effective and responsive method for maintaining water supply awareness and preventing dry-run scenarios for the pump.

9.3 Power Supply Design and Testing

In the initial phase of development, the Bio-Sense Pot system was powered by a single 3.7V Li-ion battery paired with a 5V solar panel for recharging. The battery voltage was stepped up using a boost converter to supply 5V for the ESP32 and other components. However, early testing revealed critical limitations with this configuration. Specifically, the 5V submersible water pump and 100-LED WS2812B grow light strip created substantial current demands—approximately 500mA and 6A respectively. Under these loads, the single battery depleted rapidly and was unable to maintain a stable voltage, leading to system crashes, brownouts, and erratic behavior from the ESP32 and other sensors. The limited charging current from the solar panel also proved insufficient for maintaining the battery's charge under heavy load conditions. These performance issues prompted a significant redesign of the power system to accommodate the high-current requirements and improve overall reliability.

To address these issues, the power supply system was upgraded to utilize four 3.7V 9600mAh Li-ion batteries, grouped into two separate 2S (7.4V nominal, 8.4V max) power sources. One of these sources was routed through a step-down converter (LM2596S-ADJ) to provide a stable 5V rail dedicated to powering the submersible water pump, sensors, and microcontroller components. The LM2596S-ADJ was selected for its adjustable output, robust current handling, and proven efficiency in embedded systems. By isolating the motor and peripheral power from the light system, this design minimized voltage drops and noise interference, ensuring more stable operation across the board. Testing verified that the pump activated consistently and sensors—including the soil moisture and ultrasonic units—functioned without data loss or erratic behavior, even during concurrent component operation.

The second 2S battery pack was assigned exclusively to the high-power LED lighting system and connected to a separate LM2596S-ADJ module, stepped down to 5V. This design allowed the lighting system to draw the substantial current it required—up to 6A—without affecting other components. During load testing, the LED strip remained stable across different brightness settings and duty cycles, and system temperature remained within safe operating ranges with appropriate heat dissipation. The separate power rail ensured that any transient voltage spikes or sags from the lighting load did not interfere with ESP32 functionality or sensor readings. This separation of critical loads greatly improved system performance and made power delivery far more predictable and controllable.

To support safe charging and battery management, the system incorporated the TP5100 dual Li-ion battery charging module. This module was capable of charging 2S configurations at 8.4V with up to 2A of current, making it suitable for the battery bank's capacity and allowing efficient recharging from either a solar panel or external adapter. The TP5100 was chosen for its integrated overvoltage, short-circuit, and over-temperature protection features. Bench testing confirmed that the charging cycle transitioned correctly between constant current and constant voltage phases, and it was able to fully charge the 2S packs without overheating or misreporting voltage status. The charging module was positioned in the circuit so that the batteries could be recharged while the system remained operational.

To further ensure battery health and safety, a 2S 8A BMS (Battery Management System) protection board was installed. This BMS protected each 2S battery bank against overcharge, over-discharge, and overcurrent conditions. During testing, the BMS correctly cut off output when undervoltage thresholds were reached and resumed operation once battery levels returned to safe levels. It also safeguarded the battery against accidental short circuits and prolonged heavy loads, particularly important when the lighting system was operating at full brightness. The inclusion of the BMS provided an essential safety layer, enabling the use of high-capacity Li-ion batteries in a controlled and protected manner. Together, the redesigned power architecture—comprising dual 2S battery packs, step-down converters, a high-efficiency charger, and BMS—successfully met the system's demanding energy requirements while maintaining stability, modularity, and safe operation.

Chapter 10: Administrative Content

10.1 Work Distribution

For the BioSensePot project, the work distribution among the team members is as follows:

- Brucely Charles: Responsible for the temperature and humidity sensor, the solar panel, and structure support for the pot. Brucely's focus is on ensuring the environmental sensing and energy management components are working seamlessly.
- Phuong Le: In charge of the water pump system, the water level sensor, and managing the power distribution to the components. Le will ensure proper water flow and power management for the system.
- Alex Beaufort: Will handle the software development, including coding, communication protocols, and user display systems. Alex is responsible for ensuring the interface and user interactions are smooth and functional.
- Ryan McDonnell: Focuses on the optical spectrometer, grow lights, and camera for spectrometer. Ryan will develop the components related to light spectrum analysis and the growth-light system, ensuring the plant gets optimal lighting for growth.

10.2 Project Milestones

Senior Design 1- Spring 2025			
Task	Time period	Dates	Responsibility
Project Selection	2 Weeks	01/10/2025	All
D&C Documentation	1 Weeks	1/24/2025	All
D&C Meeting With Advisors	30 Minutes	01/28/2025	All
System Design Documentation	1 week	01/30/2025	All
Circuit and Sensor Assembly	2 weeks	02/15/2025	Phuong, Brucely
Light-Seeking Algorithm Implementation	2 weeks	02/25/2025	Alex, Ryan
Watering and Environmental Monitoring	2 weeks	03/05/2025	Phuong, Brucely
Solar and Power Management System	2 weeks	03/05/2025	Alex, Ryan
Midterm report	5.5 weeks	03/24/2025	All
Prototype Integration	1 weeks	03/28/2025	All
Testing and Performance Analysis	1.5 week	04/04/2025	All
Final Report and Presentation	7-8 week	02/25/2025-04/22/2025	All

10.3 Budget and Funding Estimations

Item	Estimated Price	Quantity	Details
Microcontroller	\$29	1	A low-power microcontroller like Arduino Uno or ESP32 to control sensors and actuators.
Temperature sensor	\$6	1	A temperature and humidity sensor to collect data of temperature surrounding the plant pot.
Relay Module	\$5	1	A relay module to control high-power devices like water pumps and lights.
Water Pump	\$15	1	A low-voltage DC water pump to control watering. Suitable for small to medium-sized pots.
LED Grow Lights	\$50	1	Energy-efficient grow lights (adjustable intensity) to support plant growth.
Photo Sensor/Light Sensor	\$3	1	A simple light sensor to detect ambient light levels and trigger lighting.
Custom Spectrometer	\$50 +	1	Measures ambient light spectra to provide data for dynamic lighting adjustments.
Multi-Channel LED Driver	\$25	1	Provides independent control of grow light wavelengths.
Solar Panel	\$30	1	A solar panel to charge the system's battery and power the system (choose according to expected load).
Solenoid Valve	\$18	1	Controls water flow based on current soil moisture.
Lithium Battery	\$20	1	Rechargeable battery to store solar energy and provide power to the system during low sunlight periods.
Battery Management System (BMS)	\$10	1	A BMS to safely manage charging and discharging of the lithium battery.
Pump Valve (for	\$10	1	A valve to control the flow of water through

irrigation)			the irrigation pipe.
LCD Display (16x2 or 20x4)	\$20	1	A simple LCD screen to display sensor data (e.g., moisture, temperature, humidity).
Resistor, wires, connectors	\$10	?	Miscellaneous electronics components (resistors, jumper wires, etc.) for connections.
Enclosure Box (waterproof)	\$15	1	Protective enclosure for the electronics to ensure safety and durability in both indoor/outdoor settings.
Connectors (for sensor wiring)	\$5	?	For connecting sensors, relays, and pumps to the microcontroller.
Miscellaneous (mounting, etc.)	\$10	1	Mounting hardware, screws, and adhesives to fix sensors, components, and wiring.
Miscellaneous Cost for Safety and Debug	\$20	1	Cost for debugging, safety, and testing components, including tools.

Appendix A:

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We hereby declare that we have not copied more than 7 pages from the Large Language Model (LLM). We have utilized LLM for drafting, outlining, comparing, summarizing, and proofreading purposes.