

GreenSync: Engineering Innovation for Sustainable Agriculture



Group 12:

Roman Luknicki	Electrical Engineering
Rohit Goeptar	Computer Engineering
Thomas Parker	Electrical Engineering
Victor Arteaga Cuenca	Computer Engineering

Reviewer and Committee:

Dr. Mark Maddox
Dr. Mike Borowczak
Dr. Saleem Sahawneh
Dr. Justin Phelps

Mentor:

Dr. Lei Wei
Dr. Chung Yong Chan

Chapter 1 - Executive Summary

Future home of the summary

Chapter 2 - Project Description

2.1 Project Background

For thousands of years, agriculture has depended on the careful observation of natural elements. Early civilizations like those in Mesopotamia and along the Nile developed irrigation systems to channel water to their crops, relying heavily on environmental cues to guide planting and harvesting. The success of early farming was directly tied to how well people could monitor sunlight, soil conditions, and water availability, long before the invention of modern tools or automation. This deep-rooted relationship between humans and plants formed the basis of not only agricultural development but also societal growth.

As technology and infrastructure evolved, large-scale agriculture became more industrialized, reducing the need for individuals to grow their own food. However, interest in plants never disappeared, it simply shifted. In urban areas and residential spaces, people began caring for houseplants, small gardens, and community green spaces as a way to reconnect with nature, improve indoor air quality, and enhance living environments. In particular, the rise of indoor gardening and the popularity of houseplants in the 21st century has transformed plant care into both a creative hobby and a method of personal wellness.

This cultural shift has coincided with rapid advancements in consumer technology. The growing accessibility of sensors, microcontrollers, and open-source platforms has enabled individuals to explore how everyday tasks like watering a plant can be improved through automation and real-time monitoring. As interest in sustainability and smart living has grown, more people have turned to do-it-yourself (DIY) solutions to solve problems in their personal environments. Online communities of hobbyists and students now regularly build simple systems that integrate electronics with nature, learning engineering principles in the process.

These developments represent a fusion of traditional practices and modern innovation. While the fundamentals of plant care: light, water, and attention remain unchanged, the tools available to support those tasks have become far more advanced. The background of this project lies in that intersection: where ancient agricultural wisdom meets new technological possibilities, and where hands-on experimentation helps bring the future of home gardening to life.

2.2 Motivation

Houseplants have seen a significant rise in popularity, especially in recent years, as people seek to enhance their living environments with natural beauty, improved air quality, and a sense of calm. However, despite their benefits, many indoor plants are poorly maintained due to simple but impactful mistakes. Studies and surveys have shown that a large percentage of houseplants are lost each year due to either neglect or improper care. Among the most common issues are **overwatering**, which can lead to root rot and the proliferation of fungus gnats, and **underwatering**, which stresses the plant and inhibits growth. Additionally, **improper sunlight exposure**, whether too much or too little, can result in scorched leaves, poor color, and even plant death. These challenges are not uncommon among casual plant owners and can be discouraging, especially when plants that are meant to bring joy become a source of stress.

This dilemma inspired our group of four electrical and computer engineering students to develop a smarter, more reliable approach to plant care. As engineering students, we're constantly looking for ways to apply our technical knowledge to solve real-world problems, and this project offered the perfect intersection of embedded systems, sensor integration, power management, and user interaction design. It allows us to practice and demonstrate skills in microcontroller programming, analog and digital signal processing, and system-level integration—skills we've developed throughout our coursework and labs. The Smart Garden System not only fits well within our academic field, but also gives us the freedom to be creative and work on something that's meaningful to us personally.

Each of us has, at some point, struggled to keep a plant healthy, whether due to a busy schedule, lack of knowledge, or inconsistent conditions in our homes. This personal connection to the problem strengthens our motivation, as we want to build something that we would use ourselves. There's something deeply rewarding about nurturing a plant and watching it grow, and this project gives us

the opportunity to make that experience more accessible and successful for others.

Beyond our own interests, we recognize the broader value of plant care in households. Plants like the **snake plant** are known to filter airborne toxins such as formaldehyde, benzene, and xylene, improving indoor air quality and contributing to a healthier home. Studies have also shown that indoor plants can help reduce stress and improve mood—benefits that are especially important in today's fast-paced, often digitally overwhelming environments. Maintaining healthy plants isn't just a hobby; it's a lifestyle choice that supports wellness, sustainability, and mental clarity.

The **post-pandemic gardening boom** has also played a role in our decision. Many people began turning to indoor and balcony gardens during lockdowns as a way to stay grounded and productive. Even now, the trend of **natural living and homegrown food** continues to grow, with individuals and families looking for ways to bring a little more green into their homes. Our Smart Garden System aligns perfectly with this shift and could eventually evolve into something scalable—perhaps a larger, multi-plant system, or even a community garden platform in the future.

Ultimately, this project represents a fusion of our technical training and our appreciation for the natural world. It challenges us to think critically about automation and sustainability, while offering a product that could make a real difference in people's lives. For us, it's more than just a senior design project—it's a chance to build something practical, meaningful, and potentially expandable far beyond its initial scope.

2.3 Existing Projects

The intersection of technology and horticulture has given rise to a variety of smart plant care solutions, ranging from commercial products to DIY projects. These innovations aim to simplify plant maintenance by automating tasks such as watering, lighting, and monitoring environmental conditions.

2.3.1 Commercial Solutions

LetPot Automatic Watering System 2.0: This system automates plant watering by delivering controlled water amounts to each plant's base through adjustable drippers, all managed via a smartphone app. It's suitable for different scenarios, including indoor and outdoor plants, and offers features like customizable watering schedules and real-time monitoring.

GrowCube Smart Watering System: GrowCube is an intelligent plant watering system based on four independent soil moisture sensors and water outlets. Using an exclusive app, it allows users to monitor soil moisture in real-time and control watering accordingly. The system supports up to four plants simultaneously and provides detailed data visualization for plant care.

Click and Grow Smart Garden: Click and Grow offers a range of indoor gardening products, including the Smart Garden series. These systems use self-irrigating technology and "plant pods" containing seeds, nutrients, and a growing medium. The Smart Garden 3 and 9 models are designed for home use, while the Wall Farm can grow up to 51 plants, catering to more extensive indoor gardening needs.

Gardyn Home System: Gardyn provides a high-tech indoor gardening solution that allows users to grow up to 30 plants, including vegetables, fruits, and herbs, indoors with minimal effort. The system features full-spectrum LED lighting, AI-based plant care monitoring via the Gardyn app, and a sleek design suitable for modern living spaces.

2.3.2 DIY and Open-Source Projects

Arduino-Based Smart Gardens: Enthusiasts have developed various DIY smart garden projects using Arduino microcontrollers. These projects often include soil moisture sensors, temperature sensors, and light sensors to monitor plant conditions. For instance, one project integrates an Arduino Mega with a TFT touchscreen to display real-time data and control watering schedules.

Raspberry Pi IoT Garden: Leveraging the power of the Internet of Things (IoT), some DIY projects utilize Raspberry Pi to create smart gardens. These systems can monitor real-time status of plants, including soil moisture and temperature, and allow users to access data and control watering through a smartphone app.

OpenAg Personal Food Computer: Developed as an open-source platform, the Personal Food Computer is designed for controlled-environment agriculture. It allows users to monitor and control environmental variables such as temperature, humidity, and light, providing a comprehensive system for plant growth research and education.

2.3.3 Comparative Analysis

While commercial systems like LetPot and GrowCube offer user-friendly interfaces and plug-and-play functionality, they may come with limitations in terms of customization and scalability. On the other hand, DIY projects provide flexibility and a deeper understanding of the underlying technology but require a higher level of technical expertise and time investment.

Our proposed Smart Garden System aims to bridge the gap between these two approaches by offering a customizable, scalable, and user-friendly solution. By integrating affordable sensors, microcontrollers like the ESP32, and optional features such as solar power and mobile app integration, our system aspires to provide a comprehensive plant care solution suitable for both novice and experienced users.

2.4 Goals and Objectives

Goals:

This project aims to provide an efficient and reliable solution for monitoring and maintaining the health of indoor plants using automation, environmental sensing, and user-centered design. The Smart Garden System is intended to reduce the burden of daily plant care while promoting sustainability and increased user engagement. The platform combines hardware and software subsystems to create a modular, extensible system capable of adapting to a wide variety of plant types and environments. The goals listed below represent the broad, high-level vision for the system, with each goal followed by specific technical objectives that define the key deliverables needed to fulfill it.

Goal 1: Build an optimized plant environment for health and growth

To ensure plant longevity and promote consistent development, this goal focuses on sensing and maintaining the plant's physical environment primarily hydration and sunlight exposure through intelligent, automated responses.

- Develop a soil moisture sensing system capable of continuously monitoring the plant's hydration level.
- Implement a light intensity sensing system to measure and log the amount of ambient sunlight the plant receives throughout the day.
- Record real-time environmental data from the soil moisture and light sensors at regular intervals for analysis and feedback.
- Establish a structured data storage system to archive all recorded sensor data for long-term tracking and comparison.
- Include plant care profiles with ideal moisture and light ranges for various species, allowing the system to interpret sensor data accordingly.
- Define automated threshold logic to trigger watering or light supplementation when environmental readings fall outside optimal ranges.
- Design a stable power delivery system with support for future expansion to solar or battery options.
- Calibrate all sensors against known values to ensure accurate readings for reliable feedback control.

Goal 2: Develop a Camera System for Daily Growth Tracking

To visualize and document plant growth over time, the system will include a time-lapse camera module. This feature not only enhances user engagement but also serves as a useful tool for analyzing environmental effects on plant development. Captured images will be stored with timestamps, allowing for playback of the plant's progress over days or weeks.

- Integrate a compact, low-power camera module capable of capturing periodic images (e.g., once per day).
- Automate the image capture process using the microcontroller, triggered by a daily timer.
- Store images locally with metadata (date/time) for future retrieval and time-lapse generation
- Ensure power-efficient operation of the camera system to support long-term deployment.
- Design system architecture to allow later integration with cloud or mobile app viewing features.

Goal 3: Create a Functional Mobile Application Interface

The mobile application will serve as the primary interface for users to access their plant's environmental data in a clean and readable format. The goal is to provide users with an easy-to-understand interface for tracking their plant's condition over time without requiring complex interaction or real-time processing. This will help support user awareness and engagement while maintaining system simplicity.

- Develop a mobile app interface that displays current moisture and light readings in an organized and user-friendly format.
- Enable the app to store and display past sensor readings over time, allowing users to view environmental changes and identify patterns.
- Configure the app to receive and display data transmitted from the system's microcontroller at fixed time intervals.
- Integrate a basic plant database within the app that allows users to select their plant type and apply pre-programmed optimized care levels.

Goal 4: Create a Modular and Expandable System Design

This goal focuses on ensuring the project is built with long-term scalability in mind. By designing the hardware and software architecture to be modular, future additions such as more sensors, plant zones, or new features can be integrated with minimal rework. This also allows other developers or users to customize and

adapt the system to suit different use cases or plant types beyond the initial prototype.

- Design the system architecture to support multiple sensor inputs and actuator outputs, allowing additional plant zones to be added in the future.
- Organize the hardware layout, including the custom PCB, to allow for additional modules such as temperature sensors, humidity monitors, or alternative lighting.
- Ensure software components, including data logging and mobile interface functions, are structured to accommodate future expansion without major redesign.
- Enable clear documentation and code structure to support future teams in continuing or building upon the project after the initial implementation.

Objectives:

Project Objectives

Water Distribution System Objectives

- Deliver water to the plant using a compact pump or solenoid valve system controlled by the microcontroller
- Respond to moisture sensor data and initiate watering when hydration levels fall below a pre-set threshold
- Regulate water flow duration for each watering cycle to avoid overwatering
- Allow for simple calibration and tuning of moisture thresholds during testing and refinement

Light Management System Objectives

- Use an LED grow light to provide supplemental lighting in environments with low natural sunlight
- Activate the light module based on light sensor input and defined exposure thresholds
- Support scheduled or triggered lighting routines that simulate a healthy day-night cycle
- Ensure efficient power usage to minimize energy consumption and heat buildup

App and User Interface Objectives

- Develop a mobile application that displays soil moisture and light readings from the system
- Visualize past sensor readings through a basic history log or time stamped record system
- Allow the user to select a plant profile from a preset database with optimized care values
- Receive and display sensor data via Bluetooth communication from the microcontroller
- Create a clean and user-friendly layout tailored for casual plant owners

Camera System Objectives

- Integrate a small camera module to capture daily images of the plant
- Store images locally or forward them to the app for later viewing
- Associate each image with a timestamp to enable time-lapse creation
- Operate with low power consumption between image captures

Environmental Sensor Objectives

- Accurately measure soil moisture and ambient light conditions using reliable sensors
- Collect and log data at consistent intervals to track environmental trends
- Ensure sensor accuracy through calibration and validation during integration
- Reduce power usage by placing sensors into low-power modes between active readings

Microcontroller and System Integration Objectives

- Manage all system functions including data collection, actuator control, and communication
- Coordinate timing and logic to run the watering, lighting, and camera subsystems
- Package sensor and system data for Bluetooth transmission to the app
- Interface with a custom PCB for streamlined hardware integration and power routing

Stretch Goals / Future Additions

Notification and Alerts

- Add a mobile alert system to notify users of low moisture, poor lighting, or other plant stress indicators
- Include customizable thresholds so users can set personalized alert conditions

Environmental Expansion

- Integrate temperature and humidity sensors to monitor additional environmental factors
- Create alerts when values fall outside the optimal range for a selected plant type

Enclosed Growth Environment

- Design a mini greenhouse enclosure with passive or active climate control features
- Maintain a stable microclimate for sensitive plants or exotic species

Edible Plant Support

- Expand system profiles to support fruits, vegetables, and herbs
- Include care parameters for different growth phases like seedling, flowering, and fruiting

Modular Scalability

- Support multi-plant setups with separate sensor-actuator modules per plant
- Enable easy hardware expansion through plug-and-play connectors or addressable nodes

AI Plant Identification

- Use the onboard camera and an integrated AI model to recognize plant species
- Auto-load matching care profiles based on plant type for optimal automation

Cloud Integration

- Sync data to the cloud for backup, multi-device access, and remote monitoring
- Enable long-term trend analysis and personalized plant insights via web or mobile dashboard

Growth Analytics

- Analyze image and sensor data to estimate plant growth trends and detect early signs of stress
- Provide predictive care suggestions based on historical patterns

2.5 Description of Features & Functionalities

The smart plant care system is designed to automate and optimize the maintenance of houseplants through a user-friendly, scalable platform. Its general functionality revolves around monitoring environmental variables, delivering targeted care, and providing meaningful user feedback. This system is intended to serve both novice and experienced plant owners, offering reliable and informative features to support healthier plant growth.

A core feature of the system is its modular scalability. The initial prototype is built to support a single plant, but it is designed to expand easily to accommodate multi-plant configurations. Each module includes its own sensor suite and actuator components to ensure individual plant needs are met without interference. This allows the system to grow alongside a user's plant collection, creating a flexible long-term solution.

The system also integrates a basic user interface designed for accessibility. The UI provides real-time sensor data, historical trends, and options to configure care parameters such as light thresholds or watering schedules. For enhanced interaction, the project envisions a mobile application interface that may eventually support remote monitoring and manual overrides.

Another general capability of the system is the ability to function semi-independently when unattended. The goal is to ensure consistent plant care even while users are traveling or otherwise unavailable. Timed watering, light triggering, and data logging are all features intended to reduce the amount of manual upkeep required.

Additionally, the project is built with educational and sustainability-oriented goals. Users can learn more about their plant's needs over time and may consult a built-in database for optimal growth conditions. Power options may include standard DC supply or, in future revisions, solar panel integration for low-energy off-grid setups. Overall, the general system behavior emphasizes reliability, user empowerment, and extensibility.

2.6 Engineering Requirements:

Table 1 outlines the key engineering specifications defined for the Smart Garden System. Several of these specifications have been highlighted as testable benchmarks for the final demonstration in SD2. These values represent critical system requirements tied to core features such as automated watering, light activation, and camera capture. Each specification was selected to reflect important design priorities including power efficiency, sensor responsiveness, system scalability, and integration with typical indoor plant environments. By focusing on these essential parameters, the team can validate the system's reliability and effectiveness during development. These specifications also provide a clear framework for testing, helping identify performance gaps early and ensuring the final implementation aligns with user needs. Ultimately, this structured approach supports both a successful prototype and future system expansion.

Table 1: Specifications of Engineering Requirements

CATEGORY	PARAMETER	REQUIREMENT
Water System	Soil Moisture Polling Rate	At least once per minute
	Watering Activation Delay	Less than 10 seconds after threshold is crossed
	Water Delivery Accuracy	±10% of target watering duration
	Water Pump Flow Rate	At least 1 Liter per Minute
	Water Pump Response Time	Less than 3 seconds
	Water Reservoir Capacity	At least 500 mL
	Moisture Sensor Lifetime	At least 6 months (under standard use)
	Moisture Sensor Accuracy	±5% volumetric water content
	Water Pump Power Consumption	Less than 75 Watts
Light System	Light Sensor Polling Rate	At least once every 2 minutes
	Grow Light Power Consumption	Less than 50 Watts
	Grow Light Response Time	Less than 5 seconds
Camera System	Image Capture Frequency	Once per day
	Image Resolution	Minimum 640×480 pixels
	Image Storage Capacity	At least 30 days of daily images (locally)
	Timestamp Accuracy	Within ±1 minute of scheduled capture
	Camera Wake & Capture Time	Less than 10 seconds
User Interface	Data Sync Interval	At least once per hour
	Supported Plant Profiles	Minimum of 5 preloaded species
	Sensor Data Display Delay	Less than 15 seconds after MCU transmits
System Power	System Power Source	12V DC adapter (baseline configuration)
	Battery Life (Moisture Sensor)	At least 180 days
	Operating Temperature Range	10°C to 40°C
	PCB Expansion Support	Minimum 1 additional sensor or actuator port
	System Footprint (Single Unit)	No larger than 6" × 6" × 8"

System Demonstration Overview:

To validate the core functionality of the GreenSync smart garden system, our live demonstration will showcase the interaction between environmental sensing and automated plant care. The demonstration will highlight three key subsystems: the **Watering System**, **Lighting System**, and **Camera Module**, while referencing specific performance specifications from our engineering requirements.

-  **Watering System:** We will demonstrate real-time soil moisture monitoring and automated irrigation control. Specifically, the **Soil Moisture Polling Rate** will be shown operating at **at least once per minute**, and the **Watering Activation Delay** will be confirmed to be **less than 10 seconds** after the soil crosses its dry threshold.
-  **Lighting System:** The system will respond to simulated low-light conditions by activating the grow light within the specified **Grow Light Response Time of less than 5 seconds**. Power draw will remain below the **50-Watt maximum** for energy efficiency.
-  **Camera Module:** The demonstration will include image capture functionality with an **Image Resolution of at least 640×480 pixels**, and the captured image will include a **timestamp accurate within ±1 minute of the scheduled capture time**.

This approach ensures that the demo not only showcases functionality but also validates compliance with **critical engineering requirements** defined in our design specifications.

2.7 House of Quality

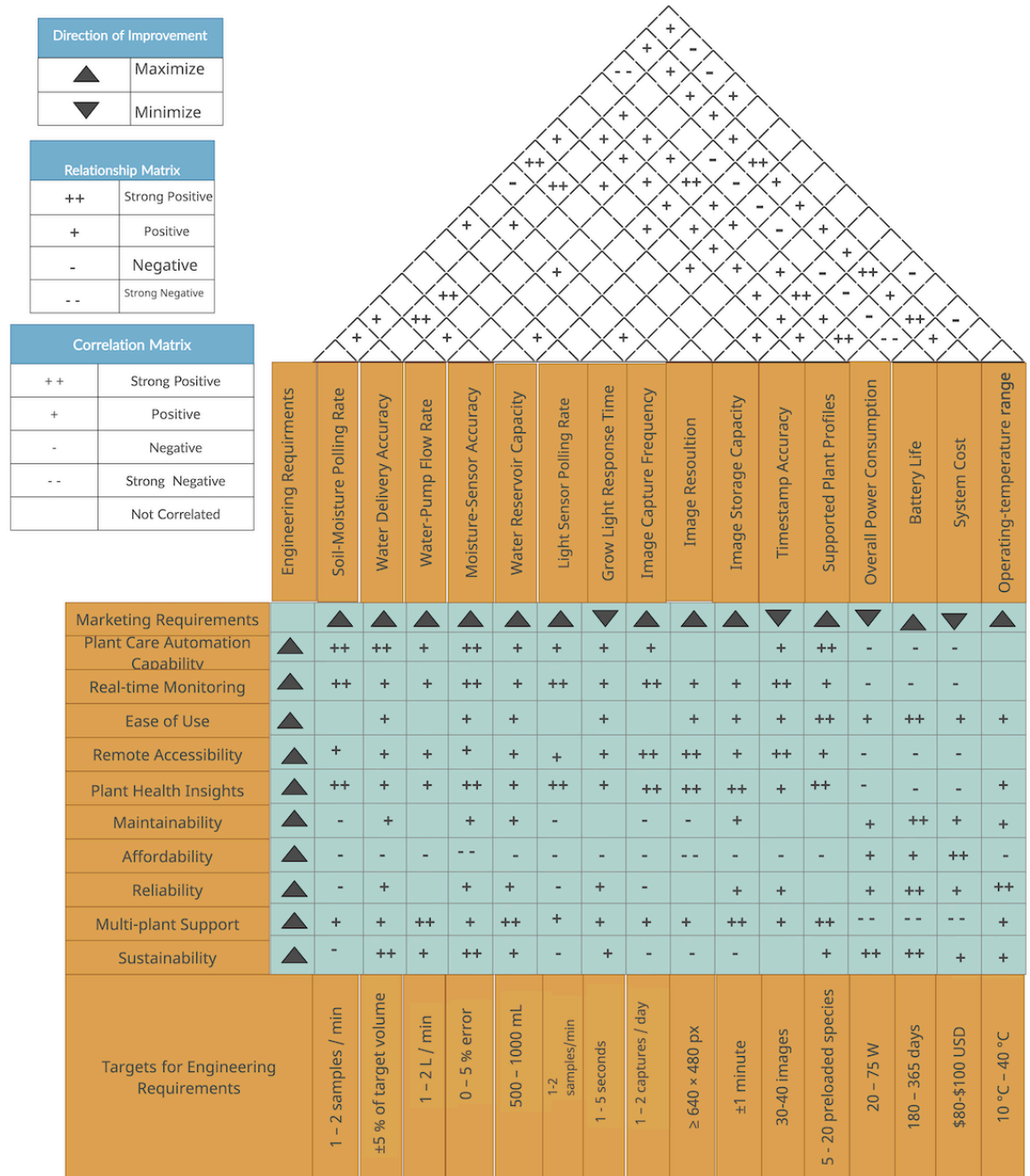


Figure 3: House of Quality

2.8 Hardware

The hardware implementation is structured around three primary subsystems: environmental sensing, plant care delivery, and growth monitoring. Each subsystem is composed of key components selected to achieve precise functionality and reliable integration.

Environmental Sensing Subsystem: This includes the soil moisture sensor and the light sensor. The soil moisture sensor is embedded in the plant's soil and is responsible for collecting data on current hydration levels, which are then transmitted to the microcontroller. The light sensor, positioned to detect ambient conditions, captures sunlight exposure levels. Together, these components allow the system to continuously monitor plant care variables and determine whether intervention is needed.

Plant Care Delivery Subsystem: This subsystem handles active plant maintenance tasks. It includes a water pump or solenoid valve system that is triggered based on sensor thresholds or time logic. A grow light module may also be included for indoor environments with insufficient natural light. These elements are connected to a custom PCB, which organizes power distribution and circuit integration. The microcontroller manages all actuator commands, ensuring that water and light are delivered in the correct amount and at the right times.

Growth Monitoring Subsystem: To add a visual element to plant progress tracking, the system integrates a compact camera module. This module captures daily images that are logged with a timestamp for future time-lapse generation. The camera's operation is controlled by the central microcontroller and configured to function at low power to accommodate continuous deployment.

Additional Considerations: The system includes a power management unit that supports either wall outlet DC input or, in extended applications, solar panel integration. All sensors, actuators, and communication modules connect through the custom-designed PCB, which also supports power regulation and expansion ports for future scalability.

While the database and user interface reside on the software side, the microcontroller and PCB enable the bridge between hardware readings and digital logging. This ensures sensor data is routed to storage and the user interface seamlessly, maintaining synchronization between physical measurements and software feedback.

2.8.1 Hardware Diagram

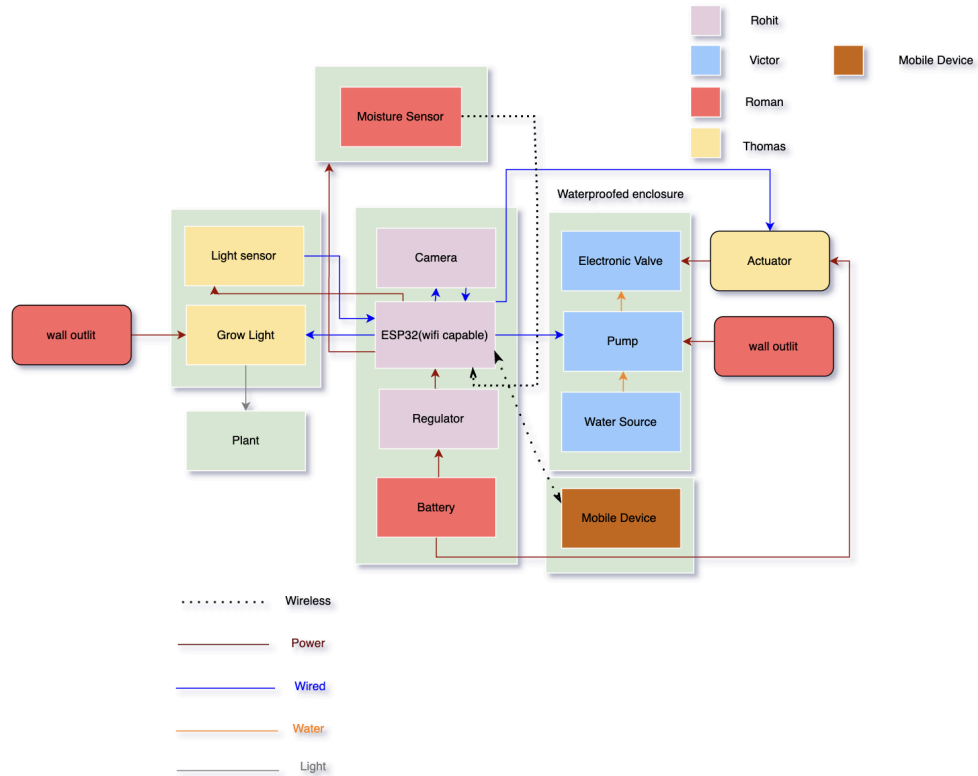


Figure 1: Hardware Diagram

2.9 Software

The software architecture of the smart plant care system is responsible for processing sensor data, executing logic for automated actions, managing user interaction, and maintaining data logs. It is divided into several core modules corresponding to the system's primary functions: sensing and data processing, care logic and actuation, image logging, and user interface management.

Environmental Data Processing:

Sensor readings from the soil moisture probe and light sensor are sampled at predefined intervals by the microcontroller's firmware. The raw analog or digital values are filtered and normalized for consistency. Threshold-based comparisons are then applied to determine if the soil is too dry or if the light level is inadequate. These results are stored locally in memory and periodically written to a database for historical tracking.

Automated Care Logic:

Based on the processed data, the software determines whether to activate the water pump and/or grow light. Watering logic can operate on two modes: threshold-based (triggered when soil is dry) or time-based (watering at set intervals). Similarly, the light module can be toggled if natural light falls below a configured lux threshold. Logic routines also include cooldown timers to avoid repeated or excessive actions. These automated decisions are coordinated by a state machine programmed on the microcontroller.

Image Capture and Logging:

The time-lapse feature is managed by a scheduled software task that triggers the camera once daily. Each image is stamped with a date and time, then saved to a local or cloud-connected storage directory. This enables long-term visual analysis of plant growth, which may be displayed in the user interface or exported externally. Storage management includes naming conventions and retention policies to avoid overflow.

User Interface and Database Integration:

All sensor readings, watering events, light activation logs, and image data are synchronized with a centralized database. This allows the mobile application to retrieve and display real-time and historical plant data. The UI provides users with tools to configure watering and lighting thresholds, view graphs of moisture/sunlight trends, browse time-lapse photos, and manually override system actions. Notifications and alerts are also generated here, informing users of critical plant conditions (e.g., low moisture or excessive heat).

Communication and Expandability:

The software includes serial, Bluetooth, or Wi-Fi communication protocols, depending on final platform selection. These channels support communication between the microcontroller and mobile application, as well as future modules such as multi-plant expansions. The codebase is modular to support scalability and eventual updates such as additional plant profiles or sensor types.

2.9.1 Software Diagram

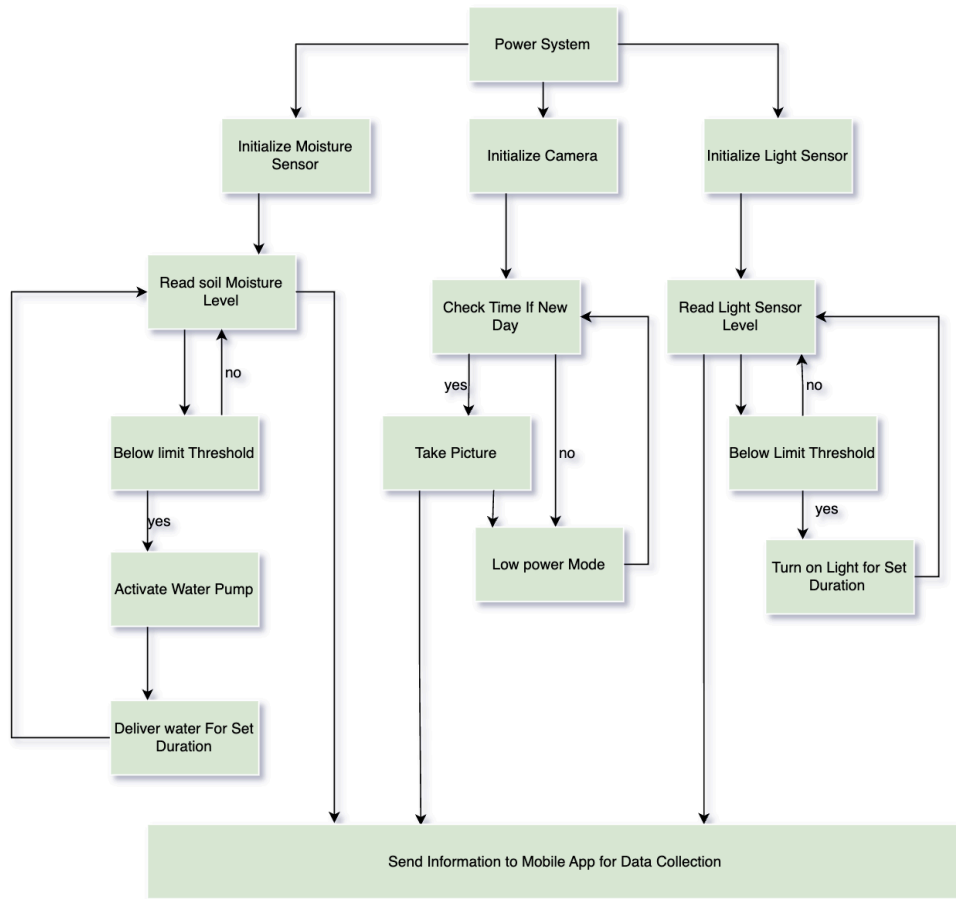


Figure 2: Software Diagram

Chapter 3 - Research

3.0 Chapter Breakdown

Before diving into the actual build of GreenSync, it's important to lay out the research that shaped our decisions. This chapter serves as the backbone of the

project, where we explore all the different paths we could've taken and explain why we chose the specific design choices and components that make up our system. Since GreenSync is a smart garden system focused on automating plant care, we needed to do more than just pick parts that looked good on paper, we had to understand how each system would work together in real-world conditions. To keep things clear and structured, we've divided this chapter into four major parts that reflect the main areas of our design thinking.

We start off in **Section 3.1** with an overview of **general systems**, this includes the core ideas behind our watering system, lighting system, and camera setup. Even though we already have a plan for how each part works, this section takes a step back to explore other possible approaches as well, just to show the range of design styles available. Then, in **Section 3.2**, we zoom into a **technology comparison**, where we talk about the types of sensing and actuation tech we looked into. Whether it's different soil moisture sensing techniques or various lighting control options, this part compares what's out there and what best fit the needs of our plant care goals.

From there, we head into **Section 3.3**, which focuses on **component comparison**. This is where we look at actual hardware options, from moisture sensors and pumps to microcontrollers and LEDs. It's not just about picking the cheapest or most popular part, it's about understanding trade-offs like power efficiency, compatibility, ease of integration, and long-term scalability. Finally, **Section 3.4** covers what we're calling **supplementary design systems**. This section includes all the extra-but-important stuff like soil types, energy sources, housing designs, and even environmental conditions that can affect how well GreenSync works over time. These are the kinds of details that don't always get much attention but can have a big impact on the success of the final product.

Altogether, this chapter gives a full picture of how much thinking and planning went into GreenSync before we ever connected a single wire or ran any code. By doing our homework and laying out each choice, we're making sure the project isn't just functional, but also informed, adaptable, and built on a solid foundation of research.

3.1 General Systems

3.1.1 Water Delivery Systems

When designing an automated plant care solution like GreenSync, one of the most critical systems to consider is how water will be delivered to the plants in a controlled, efficient, and scalable manner. While there are many ways to manually water plants, automation requires systems that can function reliably without user intervention. The delivery mechanism must balance consistency, precision, and simplicity, all while being compatible with the project's microcontroller and sensor layout. Below are five different water delivery systems that have been considered during the research and development phase.

1. Timed Drip Irrigation System

A timed drip irrigation system is a widely used method in both home gardening and commercial agriculture. This approach involves a series of tubing lines, each equipped with tiny emitters or drippers positioned at the base of the plants. The water is released slowly over time, typically regulated by a fixed schedule or timer. Some advanced systems pair the timer with environmental sensors, but many operate purely on a fixed interval basis. This system is praised for its water efficiency, as it minimizes runoff and evaporation. However, it requires careful calibration to avoid overwatering or underwatering if environmental changes occur. For GreenSync, the timed drip system is considered reliable, but it lacks the real-time adaptability that a sensor-triggered system offers.

2. Moisture-Sensor Triggered Pump System

This system forms the backbone of GreenSync's current design. It operates by constantly monitoring the soil's moisture level using a capacitive or resistive soil sensor. Once the moisture reading falls below a predefined threshold, the microcontroller activates a miniature DC water pump to deliver a precise amount of water directly into the plant's soil. This creates a responsive system that adjusts to real-world conditions rather than fixed assumptions. The biggest advantage of this approach is its flexibility — watering is only triggered when necessary, reducing waste and improving plant health. This system can be easily scaled for multiple plants by assigning individual sensor and pump pairs to each module. It also integrates cleanly with the project's ESP32 microcontroller, offering direct control and logging of watering events.

3. Gravity-Fed Reservoir with Valve Control

A gravity-fed water system uses basic physics to its advantage. By placing a water reservoir at an elevation above the plant, water can be released without a pump. Instead, an electronically controlled solenoid valve governs the flow of water. When the microcontroller receives a signal that the soil is dry, the valve opens temporarily to allow water to drain into the soil using gravity. This system is especially useful in low-power applications where using a water pump would consume too much energy. It is also a relatively quiet system compared to pump-based solutions. However, it does require thoughtful physical arrangement, such as securely mounting the reservoir above the plant level. Despite this drawback, it remains an energy-efficient and elegant solution worthy of consideration for future low-power versions of GreenSync.

4. Capillary Action (Wicking System)

Capillary watering systems, often called wicking systems, use a passive technique for hydration. A wick typically made of absorbent fabric, string, or rope connects a water reservoir to the plant's soil. As the soil dries out, it naturally pulls water up through the wick via capillary action. This method has the benefit of requiring no sensors, no microcontroller input, and no electronic components. It's extremely power-efficient and simple, making it ideal for small-scale or DIY gardening setups. However, this simplicity also means it lacks precision. The rate of water transfer is heavily dependent on environmental conditions like humidity and soil type, and it can become inconsistent over time. For GreenSync, this system offers inspiration for low-tech scenarios, but its lack of data integration and variability make it unsuitable for the goals of automation and monitoring.

5. Mist or Fog Delivery System

A more experimental option is the use of mist or fog-based water delivery. In this setup, water is atomized using either specialized nozzles or ultrasonic mist makers, delivering moisture as a fine aerosol to the plant environment. These systems are often found in high-end greenhouses or hydroponic facilities where humidity and leaf hydration need to be closely managed. Mist systems can operate continuously or be triggered by timers and humidity sensors, allowing for precise environmental control. While this approach is highly effective in controlled environments, it adds complexity and cost. Components such as misting nozzles, high-pressure pumps, or ultrasonic transducers can be difficult to integrate with compact embedded systems. For the GreenSync system, misting remains an

intriguing avenue for future development, but its current implementation favors simpler, soil-directed watering methods.

System Type	Benefits	Drawbacks
1. Timed Drip Irrigation System	- Highly water-efficient - Simple and proven in home/commercial setups - Works well with modular plant setups	- Requires precise calibration to avoid under/overwatering - Lacks real-time adaptability - Dependent on fixed schedule, not environmental feedback
2. Moisture-Sensor Triggered Pump	- Responsive to real soil conditions - Reduces water waste and improves plant health - Scalable and integrates well with microcontrollers	- Requires continuous sensor monitoring - Pump adds power consumption and noise
3. Gravity-Fed Reservoir with Valve	- Energy-efficient (no pump needed) - Quieter than pump-based systems - Simple valve control integrates easily with MCU	- Requires elevated reservoir for gravity feed - Physical design complexity (secure mounting)
4. Capillary Action (Wicking System)	- No sensors, electronics, or power required - Extremely simple and low-cost	- Inconsistent watering rate - Not suitable for data-driven or automated systems - Hard to regulate flow for different plants
5. Mist or Fog Delivery System	- Precise humidity and leaf hydration control - Common in advanced greenhouse/hydroponics setups - Scalable for high-end applications	- High complexity and cost - Difficult integration with compact embedded systems

3.1.2 🌞 Light Distribution Systems

Light plays a critical role in plant health, influencing photosynthesis, nutrient uptake, and overall growth. In indoor or controlled environments, sunlight is often insufficient or inconsistent, making it necessary to implement structured light distribution strategies. For GreenSync, the goal is to ensure reliable illumination while minimizing complexity and energy consumption. Below are five commonly used approaches to delivering and managing light for plants in smart gardening systems:

1. Natural Light Utilization

The most basic and sustainable approach is to rely entirely on natural sunlight. This method requires no additional hardware, reducing energy use and overall cost. However, it introduces major limitations in terms of consistency and control. Seasonal changes, cloudy days, and the orientation of windows can all impact light exposure, making it unreliable for autonomous plant care. While natural light can be monitored with sensors to adjust watering schedules or provide alerts, it often needs to be supplemented for consistent results.

2. Fixed Overhead Lighting

This approach places a stationary artificial light source directly above the plant, ensuring even coverage regardless of outdoor conditions. Fixed lighting systems are cost-effective, easy to implement, and integrate well with automation, as they can be controlled based on light sensor data. For single-plant or small-scale systems like GreenSync, this is one of the most practical solutions, offering predictable results without unnecessary complexity.

3. Adjustable Lighting Systems

For more advanced or multi-plant setups, adjustable lighting systems allow users to modify the position and angle of light sources as plants grow. This can be done manually or through automated rails and brackets, providing optimal light coverage for plants of different heights or arrangements. While this flexibility improves plant health and system adaptability, it requires additional hardware and potentially motorized components, increasing both cost and design complexity.

4. Modular or Clip-On Lighting

Clip-on grow lights or modular light units offer a flexible and low-cost solution for users with multiple small plants or limited space. These lights can be attached directly to pots, shelves, or other surfaces, allowing targeted lighting for individual plants. However, modular lights often lack integration with smart control systems and may not provide uniform light distribution for larger plants or grouped arrangements. Their simplicity makes them popular for casual users but less ideal for fully automated systems.

5. Dynamic Adaptive Lighting

The most advanced approach to light distribution involves dynamic control of

brightness, angle, and spectrum based on real-time sensor feedback and programmed cycles. These systems aim to replicate natural daylight patterns, including gradual intensity changes throughout the day, to promote healthy growth and flowering. While highly effective, adaptive lighting is typically used in commercial greenhouses or research environments due to its cost, complexity, and processing requirements. For a single-plant GreenSync prototype, this option represents a potential future upgrade rather than an immediate implementation.

System Type	Benefits	Drawbacks
1. Natural Light Utilization	• Zero energy cost and no additional hardware • Sustainable and eco-friendly	• Highly inconsistent (seasonal/weather-dependent) • No control over light intensity or duration • Requires ideal placement near windows
2. Fixed Overhead Lighting	• Simple and cost-effective solution • Even light coverage for single-plant setups • Easy automation with sensors and MCU control	• Limited flexibility for plant growth changes • Adds to energy consumption
3. Adjustable Lighting Systems	• Adaptable to plant height and multi-plant setups • Improves light distribution as plants grow	• Requires extra hardware and possibly motorized parts • Higher cost and design complexity
4. Modular or Clip-On Lighting	• Flexible and ideal for small or casual setups • Low initial cost and easy to reposition	• Lack of smart integration in most designs • Uneven light coverage for larger plants
5. Dynamic Adaptive Lighting	• Mimics natural daylight cycles for optimal growth • Full control over brightness and spectrum	• High cost and advanced programming required • Typically suited for large-scale/commercial systems

3.1.3 Camera Integration Techniques

Integrating camera functionality into a smart gardening system requires careful consideration of connectivity, processing capability, and storage. Unlike simply selecting camera hardware, integration focuses on how images are captured, processed, and transmitted within the system architecture. For a system like GreenSync, this involves balancing power consumption, wireless communication

needs, and compatibility with the MCU. Below are three common techniques for integrating camera modules into IoT or embedded systems.

1. Onboard MCU Integration (ESP32-CAM Approach)

This method embeds the camera and the microcontroller into a single module or PCB. In the case of ESP32-CAM, the same microcontroller that handles sensor data also captures images, stores them on a microSD card, and can transmit them via Wi-Fi. This approach minimizes wiring, reduces system complexity, and keeps costs low. However, onboard integration is limited in processing power, which makes it better suited for low-frequency tasks like daily snapshots rather than continuous streaming or advanced image processing.

2. Hybrid Integration with External Processor

In this setup, the camera module connects to a more capable device (e.g., Raspberry Pi) that processes images and handles storage or cloud uploads, while the MCU manages sensor control and actuation. This split workload allows for advanced functions like real-time image analysis or machine learning but adds complexity, cost, and power demand. Such an approach is used in research or high-end hobbyist systems where visual analytics is a priority.

3. Network-Based Integration (IP Camera Model)

Here, the camera acts as an independent IoT device that streams images or video over Wi-Fi or Ethernet to a central hub or cloud platform. This technique eliminates the need for MCU-side image processing, as most work is handled by the camera itself. While it offers scalability and remote access, it's costly and power-intensive, making it less suitable for compact embedded systems like GreenSync.

Integration Technique	Benefits	Drawbacks
1. Onboard MCU Integration (ESP32-CAM)	• Simplifies wiring and reduces cost • Compact design ideal for small-scale systems • Built-in Wi-Fi and storage support	• Limited processing power for advanced image analysis • Best suited for low-frequency snapshots
2. Hybrid Integration with External CPU (e.g., Raspberry Pi + MCU)	• Enables advanced processing like ML and analytics • Scalable for future expansion or multi-camera setups	• Higher power consumption and complexity • Increased cost and hardware footprint
3. Network-Based Integration (IP Camera)	• Independent operation with built-in streaming features • Great for large-scale or remote monitoring applications	• Expensive and power-hungry • Integration with MCU can be challenging

3.2 Technology Comparison

3.2.1 Moisture Sensing Technologies

When designing a smart gardening solution like GreenSync, one of the most essential pieces of technology is the soil moisture sensor. These devices are responsible for detecting how much water is present in the soil, helping the system make decisions about irrigation. While many users might assume there's a one-size-fits-all solution, the reality is that moisture sensing technology comes in many forms—each with unique benefits, drawbacks, and levels of precision. In this section, we explore several types of soil moisture sensing technologies that are commonly used in gardening systems, from basic resistive sensors to high-end reflectometry-based devices. Understanding these options not only helps justify our design decisions, but also paints a broader picture of how complex plant care systems can truly be.

1.Capacitive Soil Moisture Sensors

Capacitive soil moisture sensors are one of the most modern and practical technologies for detecting water levels in soil. These sensors work by measuring changes in the dielectric permittivity of the soil, which correlates directly with its moisture content. Because they avoid direct electrical contact with the soil, they are less prone to corrosion compared to older resistive models, resulting in

longer lifespan and more reliable long-term use. Capacitive sensors are ideal for microcontroller-based systems like GreenSync due to their low power requirements, analog or PWM output formats, and compatibility with most 3.3V or 5V logic systems. Their compact size and high precision make them the go-to choice for many DIY and commercial automated irrigation projects.

2. Resistive (Single-Point) Moisture Sensors

Resistive moisture sensors function by measuring the electrical resistance between two exposed probes inserted into the soil. Water conducts electricity better than dry soil, so as moisture levels increase, the resistance decreases. While these sensors are cost-effective and simple to use, they are notorious for degrading over time due to electrochemical corrosion of the probes. This makes them less ideal for long-term installations unless frequent maintenance or replacements are factored in. Despite their drawbacks, they remain popular for educational purposes and entry-level smart garden systems because of their ease of integration and very low price point.

3. Soil Water Tension Sensors (Tensiometers)

Tensiometers offer a more traditional approach by measuring the soil's water potential, or tension, which reflects how strongly water is held by soil particles. This method doesn't measure actual water content, but rather how difficult it is for plant roots to extract water. A tensiometer typically consists of a water-filled tube with a porous tip and a pressure gauge. As the soil dries, water is drawn out of the tube, creating a measurable vacuum. These sensors are commonly used in agricultural research and commercial farming. Though not always practical for compact systems like GreenSync, they offer valuable insight into plant water accessibility and are excellent candidates for discussion when analyzing precision irrigation techniques.

4. Volume Water Content Sensors (TDR and FDR)

Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) sensors determine soil moisture by measuring the time or frequency shift of a reflected electromagnetic signal as it travels along a probe. These systems offer highly accurate and repeatable measurements of volumetric water content in soil. While incredibly effective, these sensors are generally more expensive and

require more complex circuitry to operate, making them better suited for research institutions or high-end agricultural setups. Still, their inclusion in a research context helps demonstrate the cutting-edge capabilities available in soil science and automated irrigation.

5. Gypsum Block Sensors

Gypsum block sensors represent a legacy method for tracking soil moisture levels. These sensors rely on two electrodes embedded in a block of gypsum. As soil moisture permeates the block, it alters the electrical resistance between the electrodes. Gypsum has a stable and known conductivity profile, which allows for relatively consistent readings. Though not as responsive or durable as modern alternatives, gypsum blocks are still used in some agricultural environments due to their low cost and ability to mimic the water availability conditions experienced by plants. They offer a good contrast to newer digital methods and highlight the evolution of moisture sensing technology over time.

6. Moisture Sensor Arrays / Multi-Point Probes

Moisture sensor arrays use multiple sensing elements along a vertical or horizontal axis to measure moisture distribution across soil layers or plant beds. These systems are especially valuable in large-scale gardens, greenhouses, or agricultural plots where spatial variability of soil moisture plays a critical role in plant health. While overkill for small systems like GreenSync, sensor arrays introduce the concept of scalable data acquisition. They also allow for zoned irrigation, where only specific areas receive water based on localized data. Their advanced capabilities, while more complex and expensive, provide insight into how large-scale systems handle diverse soil moisture conditions effectively.

Name	How It Works	Advantages	Limitations
Capacitive Soil Moisture Sensor	Measures dielectric permittivity changes in soil	• Long lifespan • Corrosion-resistant	• Slightly higher cost than resistive sensors • Needs calibration for different soil types
Resistive Moisture Sensor	Measures electrical resistance between two probes	• Low cost • Easy to implement	• Short lifespan due to corrosion • Accuracy decreases over time
Soil Water Tension Sensor (Tensiometer)	Measures soil water tension using porous tip + gauge	• Provides soil water availability rather than just content • Good for research applications	• Bulky, requires maintenance • Slow response time
TDR/FDR (Volumetric Water Content Sensor)	Measures EM signal reflection or frequency shift in soil	• High precision and reliability	• Expensive and requires complex circuitry
Gypsum Block Sensor	Electrodes in gypsum block measure moisture resistance	• Inexpensive • Mimics plant water availability conditions	• Degrades over time • Less responsive to rapid soil changes
Multi-Point Moisture Sensor Array	Multiple sensors measure moisture at different soil depths	• Captures moisture variability across layers • Ideal for large-scale or research setups	• Expensive and complex integration • Overkill for single-plant setups

3.2.2 Light Sensing Technologies

Light sensing plays a crucial role in automated gardening systems like GreenSync by helping the system monitor and respond to environmental lighting conditions. By accurately detecting the amount of ambient light, the system can intelligently control grow lights, ensuring plants receive optimal illumination whether sunlight is present or not. A wide range of light sensors exist, each with varying levels of accuracy, response time, complexity, and cost. Below, we explore five of the most widely used light sensing technologies in embedded systems and smart garden applications.

1. Photoresistors (LDRs)

Photoresistors, or Light Dependent Resistors (LDRs), are some of the simplest and most affordable light sensors available. They work on the principle that the resistance of the material changes with light exposure—the brighter the light, the lower the resistance. These sensors produce an analog output, making them easy to read using an ADC. LDRs are well-suited for basic brightness detection and on/off control scenarios, but they lack precision and cannot measure specific light levels in units like lux. Despite their limitations, their simplicity and low power consumption make them a popular choice for beginner-level smart systems and quick prototyping environments.

2. Photodiodes

Photodiodes are semiconductor devices that generate current when exposed to light. Unlike photoresistors, photodiodes have fast response times and are capable of detecting specific wavelengths depending on their material composition. These characteristics make them more suitable for applications requiring precision and speed. However, photodiodes typically produce very small currents, often requiring amplification and analog processing circuits, which adds to system complexity. Their adaptability to different spectral ranges and reliability under various lighting conditions have kept them relevant in many embedded applications, including light monitoring in environmental and agricultural systems.

3. Phototransistors

Phototransistors are essentially light-sensitive transistors that function similarly to photodiodes but include internal gain, which boosts the output signal in response to incoming light. This makes them more sensitive and capable of detecting weaker light signals without the need for additional amplification circuitry. They tend to have slower response times than photodiodes but are easier to interface with microcontrollers. Their simple design, improved sensitivity, and cost-efficiency make them a good choice for mid-level applications requiring more sensitivity than LDRs without the complexity of high-end digital sensors.

4. BH1750 Ambient Light Sensor

The BH1750 is a digital ambient light sensor that communicates via the I2C protocol and outputs measured light intensity in lux. This sensor is widely used in

hobbyist and professional embedded systems due to its compact form factor, low power consumption, and accuracy. Unlike analog sensors, the BH1750 includes built-in calibration and processing, meaning it doesn't require ADC or complex software filtering. Its lux-based output makes it a perfect fit for applications like GreenSync, where grow light activation can be tuned based on real-world light intensity thresholds. The BH1750 is well-documented, easy to implement, and supported by a wide range of development platforms.

5. TSL2591 Digital Light Sensor

The TSL2591 is a more advanced digital light sensor that also communicates via I2C. It offers a high dynamic range and features two channels, one for full-spectrum light and one for infrared allowing for more precise calculations of visible light. It is capable of detecting light in both very low and very high brightness environments, making it highly versatile. The sensor includes onboard integration time and gain control, which can be adjusted programmatically. While it requires a bit more setup than the BH1750, the TSL2591 is ideal for smart gardening systems that demand accuracy and environmental adaptability. It is commonly used in smart lighting, horticultural monitoring, and other intelligent automation platforms.

6. Other Sensors

Other sensors worth mentioning include the Adafruit VEML7700, which shares many similarities with the BH1750 in terms of I2C communication and lux output, and is sometimes preferred for its slightly better resolution. While not covered in depth here, these alternatives provide strong backup choices when selecting the ideal light sensing solution. Ultimately, systems like GreenSync benefit most from sensors that balance ease of integration, lux precision, and low power use, with digital sensors like the BH1750 and TSL2591 leading the way.

Name	How It Works	Advantages	Limitations
Photoresistor (LDR)	Resistance drops as light increases; analog output	• Low cost • Simple implementation	• Poor accuracy • No lux measurement
Photodiode	Generates current when exposed to light	• High accuracy • Fast response	• Requires amplification • Small signals
Phototransistor	Light-sensitive transistor amplifies signal	• Greater sensitivity • No external amp	• Slower than photodiodes • Less precise
BH1750	Digital I2C sensor; outputs lux values	• Accurate readings • Easy integration	• Cannot detect IR • Basic data only
TSL2591	Dual-channel I2C sensor (visible + IR)	• High range • Precise and programmable	• Higher setup complexity • Slightly costly
VEML7700	Similar to BH1750, better resolution	• Excellent for automation • Good precision	• Minimal extra benefit over BH1750

3.2.3 💡 Types of Grow Lighting

In controlled-environment gardening systems like GreenSync, selecting the right grow light technology is critical for achieving healthy plant growth, energy efficiency, and cost-effectiveness. Unlike natural sunlight, which offers a full and balanced spectrum, artificial lighting must be carefully chosen to replicate these conditions or target specific plant needs. Each technology presents trade-offs in energy consumption, heat generation, spectral accuracy, and integration complexity. Below is a comparative overview of major grow light technologies used in indoor gardening:

1. Fluorescent Grow Lights

Fluorescent lights, including T5 and CFL variants, are affordable and provide a relatively broad light spectrum, especially rich in blue wavelengths for vegetative growth. They emit less heat than older technologies and are suitable for seedlings or small plants. However, they are bulkier and less energy-efficient than modern alternatives like LEDs, making them less practical for compact or automated systems such as GreenSync.

2. High-Intensity Discharge (HID) Lamps

HID lamps, such as Metal Halide (MH) and High-Pressure Sodium (HPS), deliver very high light intensity, which is advantageous for large-scale or commercial operations. MH lamps favor blue light for vegetative stages, while HPS emits more red/orange light for flowering. Despite their power, HID lights produce substantial heat, require ventilation, and consume significant energy, disqualifying them from small-scale smart systems focused on efficiency.

3. LED Grow Lights

LED technology dominates modern indoor gardening due to its exceptional energy efficiency, long lifespan, and adaptability. LEDs can deliver full-spectrum light or targeted wavelengths like red and blue, essential for photosynthesis. They run cool, integrate easily with automation, and work well with low-voltage microcontroller systems. For GreenSync, LEDs are the most practical and cost-effective solution for sustained performance and minimal energy use.

4. Incandescent Grow Bulbs

Incandescent bulbs are largely obsolete for serious plant care. They produce a continuous spectrum biased toward red light, but their inefficiency and excessive heat output make them unsuitable for prolonged use. Their short lifespan and low performance render them impractical for modern automated systems beyond basic experimentation.

5. Plasma Grow Lights

Plasma lighting represents a high-end solution that mimics natural sunlight with a near-complete spectrum. While excellent for specialized research or premium horticulture, these lights are expensive, power-hungry, and require complex drivers, making them unrealistic for compact home systems like GreenSync. They are better suited for large-scale greenhouses or laboratories.

6. Infrared (IR) Lighting

Infrared light extends beyond the visible spectrum and is not directly used for photosynthesis. However, it influences plant morphology, promoting structural growth and accelerating developmental stages. IR is typically integrated into full-spectrum LED arrays rather than used alone. While interesting for advanced plant care, IR technology is optional for GreenSync and is generally reserved for highly specialized systems

Name	How It Works	Advantages	Limitations
Fluorescent	Emits broad-spectrum light, strong in blue wavelengths	- Affordable - Low heat - Decent spectrum	- Bulky - Less efficient than LEDs
HID (MH/HPS)	High-intensity discharge lamps; MH=blue, HPS=red	- Powerful output - Good for large areas	- High heat - High power use - Ventilation needed
LED	Semiconductor diodes; customizable full-spectrum	- Energy-efficient - Long life - Low heat	Higher upfront cost vs fluorescent
Incandescent	Filament-based, continuous red-biased spectrum	- Very cheap - Simple	- Extremely inefficient - High heat - Short lifespan
Plasma	Gas arc lamp mimics natural sunlight spectrum	- Excellent spectrum - High performance	- Very expensive - Complex drivers - High power draw
Infrared (IR)	Emits radiation beyond visible light spectrum	- Influences plant morphology - Boosts growth	- Not for photosynthesis - Risk of heat stress

3.2.4 Camera Hardware

Monitoring plant growth through image capture is a valuable feature in modern smart gardening systems. While many projects rely solely on sensor data, cameras provide a visual record of growth, enabling users to validate sensor readings and create engaging time-lapse sequences. Several hardware solutions exist, ranging from simple consumer-grade devices to specialized embedded modules. The choice depends on size constraints, power requirements, and integration complexity. Below are five common camera hardware approaches considered during GreenSync's research phase.

1. USB Webcam Systems

USB webcams remain one of the most straightforward solutions for image capture, particularly in hobbyist projects. These devices are widely available,

affordable, and easy to program using standard operating systems such as Linux or Windows. They connect via USB to a processing device, like a Raspberry Pi, and can capture periodic still images or stream live video. While simple to implement, this option requires a separate controller or computer, adding to the overall system size and power consumption.

2. ESP32-CAM Module

The ESP32-CAM is a compact embedded solution combining an ESP32 microcontroller with an onboard OV2640 camera. It supports Wi-Fi connectivity, local storage on a microSD card, and scheduled image capture, making it highly suitable for integrated IoT applications. Its low power consumption and small footprint allow it to fit into tight enclosures, making it the preferred choice for systems like GreenSync that aim for minimal wiring and modularity.

3. IP Camera / Wi-Fi Camera Modules

IP cameras are standalone units that offer high-resolution image capture and wireless data transmission. These cameras typically include their own processing hardware and often provide features such as remote viewing via mobile apps. While convenient, they are more expensive than other options and harder to integrate with custom automation logic without relying on APIs. Their use is common in advanced monitoring systems or greenhouse applications.

4. PTZ (Pan-Tilt-Zoom) Cameras

For larger plant setups or commercial greenhouses, PTZ cameras offer flexibility by allowing remote adjustment of viewing angles and zoom. They can monitor multiple plants from a single vantage point, reducing the need for multiple cameras. However, PTZ cameras introduce mechanical complexity and higher power demands, making them impractical for compact smart gardens like GreenSync but relevant as a potential upgrade for future scalability.

5. DSLR or Mirrorless Camera with Timed Triggers

Professional cameras represent the high end of plant imaging solutions, offering superior image quality and low-light performance. These setups are typically used in research or artistic time-lapse photography projects. Integration usually requires additional hardware like remote shutters or microcontroller-driven triggers. While ideal for specialized use cases, these cameras are too costly and cumbersome for consumer-level automated systems.

Name	How It Works	Advantages	Limitations
USB Webcam	Connects via USB to PC/Raspberry Pi for image capture	• Cheap • Easy setup • Good for prototyping	• Requires external computer • Higher power
ESP32-CAM	Built-in MCU + camera + Wi-Fi, supports microSD	• Compact • Low power • Fully integrated	• Limited image quality • No PTZ features
IP Camera	Standalone Wi-Fi camera with onboard processing	• High resolution • Remote access	• Expensive • Harder to integrate with MCU logic
PTZ Camera	Motorized pan/tilt/zoom for wide-area monitoring	• Adjustable view • Scalable for big setups	• Complex • Costly • High power demand
DSLR/Mirrorless	Professional camera with timer or MCU trigger	• Excellent image quality • Advanced control	• Very expensive • Bulky • Impractical for compact systems

3.2.5 Communication & Integration Methods

Efficient communication and seamless sensor integration form the backbone of any smart gardening system. For GreenSync, these elements dictate how well data flows between components, how quickly the system responds to changing conditions, and how scalable the design can become in future versions. Communication encompasses two main areas: **wireless protocols** that enable data exchange between the system and the user interface, and **hardware-level integration methods** that connect sensors and actuators to the microcontroller. Both layers must work together to ensure consistent, low-latency, and energy-efficient performance. Below, we examine the most relevant techniques for communication and integration in smart garden applications like GreenSync.

Wireless Communication Protocols

These protocols enable data transfer between GreenSync's MCU (ESP32) and external devices such as mobile applications or cloud services.

1. Wi-Fi (IEEE 802.11)

Wi-Fi is one of the most widely used communication protocols in IoT systems, enabling real-time monitoring and remote control over local networks or the internet. For GreenSync, Wi-Fi provides the convenience of accessing data from a mobile app or browser without additional hardware. While it offers high bandwidth and easy integration, its relatively high power consumption makes it best suited for systems with stable, continuous power sources.

2. Bluetooth Low Energy (BLE)

BLE excels in low-power, short-range communication, making it ideal for direct connections between GreenSync and a user's smartphone. BLE offers quick pairing, low energy draw, and strong compatibility with mobile applications. Its limitations include reduced range and bandwidth compared to Wi-Fi, which can restrict its usefulness for cloud-based features.

3. LoRa (Long Range Radio)

LoRa provides ultra-long-range, low-power connectivity ideal for large-scale gardens or remote monitoring scenarios. While its data rate is slow compared to Wi-Fi, it allows transmission of essential sensor data over kilometers with minimal energy use. Although not necessary for GreenSync's small-scale prototype, LoRa highlights the system's potential scalability.

4. Zigbee (IEEE 802.15.4)

Zigbee enables mesh networking, making it highly reliable for multi-node environments such as greenhouses. It supports low-power, low-data-rate applications and self-healing networks. While its complexity and extra hardware requirements make it less practical for GreenSync's current iteration, Zigbee could support future modular expansions.

Name	How It Works	Advantages	Limitations
Wi-Fi	Wireless protocol for local network/internet connectivity	• High bandwidth • Easy setup • Remote access	• High power use • Needs stable Wi-Fi
BLE	Low-energy Bluetooth for short-range device pairing	• Low power • Mobile-friendly • Fast pairing	• Limited range • No cloud support
LoRa	Long-range low-power radio for transmitting small data	• Excellent range • Minimal energy use	• Very low data rate • Extra hardware cost
Zigbee	Mesh networking protocol for multi-device ecosystems	• Scalable • Self-healing networks • Low power	• Higher complexity • Extra setup required

Sensor Integration Methods

Hardware-level integration determines how sensors and peripherals connect to the microcontroller.

1. Direct GPIO Integration (Analog/Digital)

Basic sensors can connect directly to GPIO pins, with analog sensors requiring the microcontroller's ADC for reading variable voltage levels. This method is simple, cost-effective, and ideal for small systems like GreenSync, though it becomes difficult to scale with many sensors due to pin limitations.

2. I²C (Inter-Integrated Circuit)

I²C is the preferred protocol for connecting multiple sensors using only two lines (SDA, SCL). Devices like light sensors, RTC modules, and OLED displays often use I²C, making it an efficient, space-saving solution for smart garden projects. It's slower than SPI but supports easy expansion.

3. SPI (Serial Peripheral Interface)

SPI offers high-speed communication, making it ideal for data-heavy components like SD cards or camera modules. While it requires more wiring than I²C, SPI ensures stable and fast transfers for critical peripherals in GreenSync.

4. UART (Universal Asynchronous Receiver-Transmitter)

UART enables point-to-point serial communication using TX and RX lines. It's frequently used for debugging and connecting modules like Wi-Fi or GPS receivers. Although simple and efficient, UART is less scalable for multiple devices compared to I²C or SPI.

5. Wireless Sensor Integration

Some advanced systems use wireless integration to eliminate physical wiring altogether, employing Wi-Fi or BLE-enabled sensor modules. This method provides maximum flexibility and scalability but increases power requirements and software complexity, making it more suitable for future GreenSync upgrades.

Name	How It Works	Advantages	Limitations
Direct GPIO	Sensors connect directly to MCU pins; analog uses ADC	• Simple • Cost-effective • Minimal components	• Poor scalability • Pin limits • Less modular
I ² C	2-wire bus for multiple devices (SDA, SCL)	• Space-saving • Easy expansion • Widely used	• Slower than SPI • Possible address conflicts
SPI	High-speed 4-wire protocol for peripherals	• Fast, stable • Ideal for SD cards, cameras	• More wiring • Higher complexity
UART	Serial TX/RX communication for point-to-point links	• Simple • Good for debugging and modules	• Not scalable for multiple devices
Wireless	Uses Wi-Fi/BLE-enabled sensor modules for no wires	• Flexible • Supports modular designs	• High power use • Software complexity

3.2.6 Data Logging & Storage Options

In any embedded system that collects data or interacts with user commands, the question of how to store, retrieve, or transmit that data becomes a key design consideration. In GreenSync, where real-time environmental data from sensors like moisture levels or light intensity may be recorded, the system requires a reliable and practical data storage solution. This section explores various types of storage technologies that can be implemented in microcontroller-based systems,

from traditional removable options like microSD cards to more compact or cloud-based alternatives. While the final implementation in GreenSync may not use all of these methods, understanding the range of technologies available can help inform decisions about scalability, power usage, and ease of user access.

1. microSD Card Modules

MicroSD cards are one of the most popular data storage solutions for microcontroller projects, particularly when moderate to large amounts of data need to be stored locally. These cards are non-volatile, meaning they retain data even when the system is powered off. Modules are readily available that allow seamless interfacing between a microSD card and an ESP32 using SPI communication. In the context of GreenSync, this method is especially useful for storing camera images, sensor logs, or timestamped watering records that users may want to extract later. It also offers the advantage of being removable, allowing users to physically retrieve data without needing Wi-Fi or app integration. However, this flexibility comes at a slight cost of higher power consumption and the need to manage file systems (typically FAT32) using libraries like `SD.h` or `SD_MMC`.

2. EEPROM (Electrically Erasable Programmable Read-Only Memory)

EEPROM is a small-scale, non-volatile storage technology often embedded directly into microcontrollers. It is ideal for storing persistent values such as configuration settings, calibration constants, or last known states. Unlike microSD cards, EEPROM has a very limited storage capacity—typically measured in bytes or kilobytes—and is not suited for high-volume logging. In GreenSync, EEPROM could be used to remember the last time a plant was watered or to store Wi-Fi credentials for connecting to the network after reboot. While it has limited write cycles (often around 100,000), for occasional data updates it remains a reliable and battery-friendly option. The ESP32 doesn't have native EEPROM, but it emulates this using flash memory blocks.

3. Flash Memory (Internal to MCU)

Flash memory is built directly into the ESP32 and is primarily used to store program code and firmware. However, portions of it can be allocated for user data as well. This makes it a convenient option for storing logs, credentials, or sensor thresholds without the need for extra hardware. The ESP32's flash memory is usually divided into partitions, and developers can reserve a section

(commonly referred to as SPIFFS or LittleFS) to store files or configuration data. While internal flash provides an elegant, self-contained storage method, it has limitations in terms of write endurance and total capacity, especially when frequent writes are involved. For projects like GreenSync, flash memory is useful for lightweight data persistence, although not recommended for tasks like frequent image saving or detailed sensor logs.

4. Cloud-Based Storage via Wi-Fi Connectivity

Cloud-based storage solutions allow data to be transmitted from the microcontroller to an external server or cloud service such as Google Firebase, AWS IoT Core, or Adafruit IO. This method enables real-time remote monitoring, backups, and scalable storage without relying on local physical media. In GreenSync, cloud storage could be leveraged to log soil moisture trends, light exposure patterns, or camera snapshots that users can view from anywhere through a mobile app or dashboard. While it eliminates the need for physical retrieval of data, this method introduces dependency on internet connectivity and higher power usage during transmissions. Additionally, it may require authentication layers and backend development, making it more complex than local alternatives. However, in terms of scalability and user accessibility, cloud storage is among the most forward-thinking options available.

5. External FRAM Modules (Ferroelectric RAM)

FRAM (Ferroelectric RAM) is a non-volatile memory type known for its high endurance and fast read/write speeds. Unlike EEPROM and Flash, FRAM can be written to nearly unlimited times, making it ideal for applications where sensor data needs to be logged frequently without wearing out the memory. FRAM also consumes less power and doesn't require the time delays associated with Flash or EEPROM writes. Although still less common and more expensive than traditional memory types, FRAM modules (such as those by Adafruit or Cypress) can be integrated with microcontrollers like the ESP32 via I2C or SPI. In GreenSync, this technology could theoretically be used for continuous logging of moisture or lighting data across multiple time intervals. It's particularly appealing for future-proofing systems designed for long-term deployment with minimal maintenance.

6. USB-Enabled External Drives or Interfaces

While more rare in microcontroller-scale projects, it is technically possible to

interface USB storage devices or external hard drives using dedicated USB host shields or specialized MCUs. These setups allow for enormous storage capacity and could support the collection of high-resolution images, video, or long-term logs. However, integrating full USB mass storage protocols with something like the ESP32 requires careful hardware and software setup, typically including power regulation and filesystem handling. For a project like GreenSync, this level of storage is generally excessive, but it's a valuable concept when considering advanced versions of the system with expanded features like time-lapse video storage or AI image processing. Although impractical in the current version, it serves as an interesting high-capacity storage option in broader design considerations.

Name	How It Works	Advantages	Limitations
MicroSD Card	Removable card using SPI; stores images/logs locally	• Large storage • Removable • Easy retrieval	• Higher power • Requires filesystem handling
EEPROM	Small-scale non-volatile memory for configs/calibration	• Persistent storage • Low power	• Very limited capacity • Limited write cycles
Flash Memory	Built-in MCU memory for lightweight file storage	• No extra hardware • Convenient	• Limited endurance • Not for heavy logging
Cloud Storage	Sends data to online servers via Wi-Fi	• Remote access • Scalable • Real-time monitoring	• Internet-dependent • Higher power • Complex setup
FRAM	High-endurance non-volatile memory via I ² C/SPI	• Fast writes • Unlimited endurance • Low power	• Expensive • Less common • Small modules
USB Storage	Interfaces with USB drives via USB host shields	• Huge capacity • Supports video and large logs	• Complex integration • High power • Impractical now

3.2.7 User Interface Technologies

When developing a smart gardening solution like GreenSync, the way users interact with the system becomes just as important as the sensors and hardware behind it. Whether a user wants to quickly check if their plant needs watering or fine-tune environmental conditions, a reliable and intuitive user interface is key. In today's tech landscape, there are many different options for building a user interface, each with its own benefits and limitations. Some interfaces focus on visual dashboards that offer a wide range of controls and data, while others prioritize simplicity or remote access. This section explores different approaches to how users can interact with the system and monitor plant health, from mobile apps to physical buttons.

1. Mobile Application Interface (Custom App)

A custom mobile application is one of the most modern and user-friendly approaches for managing smart systems like GreenSync. These apps can be developed for Android, iOS, or both, and provide a full graphical user interface (GUI) where users can view live sensor data, receive alerts, adjust watering schedules, and even manually control devices like the water pump or grow light. Apps can connect via Bluetooth Low Energy (BLE) or Wi-Fi, depending on the system architecture. For GreenSync, a BLE-based app could offer easy pairing and local communication without needing an internet connection. With the rise of no-code and low-code development platforms such as MIT App Inventor or FlutterFlow, it's become increasingly accessible to create lightweight apps that communicate with ESP32 microcontrollers. These apps offer a clean and interactive experience while giving users total control over their system from the convenience of a smartphone.

2. Web Dashboard (Hosted or Local)

Another highly flexible and accessible UI option is a browser-based web dashboard. This method allows users to connect to a local IP address hosted by the ESP32 itself or to a cloud-hosted page where real-time data is streamed and displayed in a structured format. These dashboards can feature interactive graphs, manual control toggles, data logs, and configuration menus. For instance, a simple HTML/JavaScript page could be served directly from the ESP32's SPIFFS or SD card, requiring no additional apps or downloads. Alternatively, more advanced dashboards using platforms like Firebase or

Node-RED allow for global access and secure data storage. The advantage of a web dashboard is its platform independence—users can access it from any device with a web browser, including laptops, tablets, and phones, making it a very versatile solution.

3. Serial Console Interface (USB or UART)

For debugging, initial setup, or low-level manual control, a serial console interface is an essential and timeless option. It's the simplest form of user interaction—connecting the ESP32 to a computer via USB and using tools like the Arduino Serial Monitor, PuTTY, or RealTerm to communicate directly. Through this method, users can issue commands, receive real-time output from the system, and observe debug messages that help with development and testing. While not suitable for everyday end-users, serial console interfaces are indispensable during prototyping and troubleshooting phases. They are also beneficial in educational contexts, where students can see raw data streams and understand how the system behaves behind the scenes. Despite being text-based and minimalistic, the serial console plays a foundational role in the development process.

4. Physical Interface (Buttons and LEDs)

For ultra-simplified or minimal setups, physical user interfaces using buttons, switches, and LEDs offer an intuitive and tactile way for users to interact with the system. These components are hardwired directly to the microcontroller and can be programmed to trigger specific actions—like initiating a manual water cycle, resetting the system, or toggling grow lights. LEDs, on the other hand, provide instant visual feedback, such as flashing red when moisture is low or glowing green when the system is operating normally. This method is ideal for users who don't want to rely on phones or web apps, or for environments where digital connectivity is limited. While limited in data visualization and interactivity, physical interfaces are cheap, reliable, and extremely user-friendly for basic interactions. For systems like GreenSync, adding a few well-placed buttons and indicator lights can enhance usability without adding much complexity or cost.

5. Voice Control Interface (via Assistant Platforms)

With the growing integration of smart home ecosystems, voice control is becoming a novel yet increasingly popular way to interface with IoT devices. Using platforms like Amazon Alexa, Google Assistant, or Apple Siri, users can

trigger commands or request status updates via spoken instructions. This can be accomplished by creating custom skills or routines that interface with the ESP32 through cloud services like IFTTT or Home Assistant. For example, a user could say, “Alexa, check soil moisture,” or “Hey Google, water my plant,” and the system would respond accordingly. While more complex to implement—often requiring additional setup, internet access, and third-party accounts—voice control offers an accessible and futuristic method of interaction. It also expands usability for users with limited mobility or vision, making the system more inclusive overall.

6. SMS-Based Control and Notifications

SMS-based interfaces allow users to interact with the GreenSync system via simple text messaging. Through GSM or LTE modules, the system can send status updates (e.g., "Soil moisture low: 18%") and even respond to basic commands ("WATER NOW"). This technique is particularly useful in remote locations where Wi-Fi may be unavailable but cellular service is accessible. SMS control is lightweight and requires no smartphone app or internet connection, which makes it surprisingly robust and user-friendly in specific use cases. Though limited in functionality compared to app or web-based UIs, SMS interfaces are dependable and especially practical for agricultural deployments or off-grid gardening systems.

Name	How It Works	Advantages	Limitations
Mobile App	Custom app for Android/iOS; connects via BLE or Wi-Fi	• Full control • Intuitive GUI • Real-time data	• Requires app development • Needs smartphone
Web Dashboard	Hosted locally or via cloud; accessed in a browser	• Platform-independent • No downloads needed	• Requires hosting setup • Less offline capability
Serial Console	Direct USB/UART text interface for debugging	• Simple • Reliable • Great for development	• Not user-friendly for end users • Wired only
Physical Buttons/LEDs	Hardware controls for basic functions; LEDs for feedback	• Low cost • Simple • No connectivity required	• Limited functionality • No detailed data
Voice Control	Integrates with Alexa/Google Assistant via cloud routines	• Hands-free • Accessible • Modern smart-home feel	• Complex setup • Internet-dependent • Extra APIs
SMS Interface	Uses GSM/LTE to send commands and receive system alerts	• Works without Wi-Fi • Simple user access	• Limited commands • Requires cellular module

3.3 Component Comparison

3.3.1 ESP32 Microcontroller (MCU)

In any smart system like GreenSync, the microcontroller serves as the brain of the operation, taking in sensor data, making decisions, and sending commands to actuators like pumps or lights. Choosing the right MCU is critical for balancing performance, connectivity, cost, and power consumption. While we ultimately decided on the ESP32 due to its robust features and wireless capability, this section will explore several popular microcontrollers that were considered during the design process. The comparison will evaluate core features such as processing speed, I/O capabilities, wireless support, ease of development, and cost-effectiveness to justify the final selection.

1. Arduino Uno (ATmega328P)

The Arduino Uno is often the go-to choice for beginners and prototyping due to

its simplicity, massive community support, and reliable 8-bit ATmega328P chip. It offers 14 digital I/O pins (6 PWM), 6 analog inputs, and operates at 16 MHz with 32 KB of flash memory. However, its biggest limitation lies in its lack of built-in wireless communication and relatively limited processing power. For simple automation tasks it can suffice, but for a smart garden system requiring Wi-Fi or Bluetooth, data handling, and real-time processing, the Uno quickly shows its age.

2. Raspberry Pi Pico

The Raspberry Pi Pico is a newer low-cost 32-bit MCU built on the RP2040 chip. It boasts dual ARM Cortex-M0+ cores running at up to 133 MHz, 264 KB of SRAM, and flexible I/O including I2C, SPI, and UART. While the Pico is very powerful for its price, it lacks built-in Wi-Fi or Bluetooth, meaning you'd need additional modules to enable wireless communication. For a wired or locally embedded garden system, it could work well, but the extra effort to get wireless data transmission made it less attractive for GreenSync.

3. ESP8266

The ESP8266 was considered due to its excellent cost-to-performance ratio and built-in Wi-Fi capabilities. Running at 80–160 MHz with a Tensilica L106 core, it's more powerful than the Arduino Uno and great for lightweight IoT applications. However, it has fewer GPIO pins and only a single ADC channel, limiting its ability to handle multiple sensors or actuators without expanders. For basic remote monitoring it excels, but its limitations in multitasking and lack of native Bluetooth support pushed us toward a more flexible solution.

4. STM32 "Blue Pill" (STM32F103C8T6)

The STM32 Blue Pill is a popular low-cost 32-bit ARM Cortex-M3 MCU offering impressive performance at 72 MHz, with 64 KB flash and 20 KB SRAM. It includes a wide range of communication protocols and analog peripherals. However, it lacks built-in wireless and has a steeper learning curve due to its more complex setup and development environment. For GreenSync, this added complexity wasn't worth the tradeoff, especially when simpler wireless-ready boards existed.

5. ESP32

The ESP32 is a dual-core 32-bit microcontroller with integrated Wi-Fi and

Bluetooth, making it the standout candidate for GreenSync. It supports up to 240 MHz clock speed, has 520 KB SRAM, multiple ADC channels, PWM outputs, capacitive touch sensors, and robust power-saving modes. It excels in scenarios requiring real-time data processing, wireless communication, and multitasking — all necessary for managing sensors, lighting, and a mobile app simultaneously. The ESP32 also integrates seamlessly with camera modules, making it a one-board solution for nearly every function we need. Its balance of power, flexibility, wireless features, and low cost made it the clear winner.

3.3.2 🌱 Capacitive Soil Moisture Sensor

Soil moisture sensing is a cornerstone of any automated gardening system, especially in precision-based designs like *GreenSync*. Selecting the right type of sensor plays a significant role in ensuring accurate readings, minimal maintenance, and long-term reliability. While we ultimately selected the widely used Capacitive Soil Moisture Sensor v1.2, it's important to explore other moisture sensor options to understand why this particular model is the most practical for our application. Below is an overview of five commonly used soil moisture sensing components that represent various technologies, price points, and levels of complexity.

1. Capacitive Soil Moisture Sensor v1.2

This is the sensor we've chosen for *GreenSync* due to its accuracy, durability, and compatibility. It works by detecting changes in the dielectric permittivity of the soil to infer moisture levels, and it avoids direct current flow through the soil—unlike resistive models. As a result, it experiences far less corrosion, offering a longer operational life. With a simple analog output, it integrates seamlessly with the ESP32 and operates reliably at 3.3V or 5V. Its slim profile also makes it easy to install in potted plants or confined garden areas.

2. Generic Resistive Soil Moisture Sensor

These low-cost sensors work by measuring the resistance between two exposed metal probes. As the soil becomes wetter, the resistance drops. They're extremely budget-friendly and ideal for short-term or educational projects. However, the main drawback is their susceptibility to corrosion due to electrolysis, especially in continuous-use setups. Because of this, they require

regular calibration and occasional replacement. We opted against this style due to long-term durability concerns.

3. DFRobot Capacitive Moisture Sensor

This is an upgraded version of the standard capacitive sensor, designed with better PCB coating and improved analog stability. It shares the same fundamental operating principles as the v1.2 but is known for delivering more consistent readings and better protection in outdoor or humid environments. While slightly more expensive, it's a solid option for long-term, higher-end systems. This sensor was briefly considered but passed over to maintain a lower bill of materials cost.

4. Chirp I2C Soil Moisture Sensor

Unlike analog sensors, the Chirp uses I2C communication and is fully digital. It measures both moisture and temperature and can even play a chirping sound when the plant is dry—hence the name. It also supports capacitive detection and is popular in hobbyist setups. While it offers reliable digital communication, it complicates the I2C bus and isn't as compact or straightforward as the v1.2 for our use case. Still, it's a clever example of an all-in-one sensor system.

5. Vegetronix VH400 Soil Moisture Sensor

This premium sensor outputs an analog voltage based on volumetric water content and offers high accuracy, fast response, and a waterproof build. It's often used in agriculture or research environments where precision is key. However, it comes with a much higher price tag—often 5 to 10 times the cost of basic capacitive sensors—which made it impractical for our compact, cost-effective system. Nevertheless, it serves as an excellent benchmark for top-tier performance in soil sensing.

3.3.3 Ambient Light Sensor

Light sensing is an important component of any automated garden system because it allows the microcontroller to make decisions based on current ambient lighting conditions. These sensors help determine whether grow lights need to be activated or if the natural sunlight is sufficient. There are a variety of

ambient light sensors available today, ranging from simple analog components to advanced digital devices that communicate via I2C. Each option offers its own strengths in terms of cost, accuracy, range, and ease of integration. In this section, we will explore several types of light sensors that could be integrated into the GreenSync system and evaluate them based on practicality, performance, and compatibility with our overall design goals.

1. Photodiode Sensors

Photodiodes are semiconductor devices that convert light into current. As light intensity increases, the current output increases accordingly. They are commonly used in light measurement applications due to their fast response times and excellent linearity. However, they typically produce a very small current output, which requires amplification and ADC conversion before being read by a microcontroller. This can complicate the design slightly for beginners, but they offer excellent performance in controlled settings. Photodiodes are ideal in scenarios where precise detection of light intensity changes is necessary, although they often require supporting circuitry that adds to system complexity.

2. Photoresistors (LDR - Light Dependent Resistors)

Photoresistors change their resistance based on the amount of light they are exposed to. These sensors are incredibly inexpensive and easy to use, making them popular in beginner-level Arduino and IoT projects. However, LDRs are not particularly accurate or fast, and their readings can drift over time or due to temperature changes. For simple daylight detection, they get the job done, but their lack of precision and digital interfacing makes them less suitable for a system like GreenSync where consistent feedback is essential. Nonetheless, they are still worth discussing as an entry-level baseline option.

3. Phototransistors

Phototransistors function similarly to photodiodes but with built-in amplification, meaning they can produce a stronger electrical signal in response to light. This makes them easier to integrate into circuits without needing external op-amps or complex analog-to-digital conversion. Phototransistors are sensitive and reliable but generally lack the broad measurement range or lux calibration found in digital light sensors. They are a solid choice for light detection in hobby-level applications but may fall short in precision when compared to more modern digital sensors.

4. BH1750 Ambient Light Sensor

The BH1750 is a digital light sensor capable of measuring light intensity in lux with high accuracy. It communicates via the I2C protocol, making it easy to interface with the ESP32 or other microcontrollers. This sensor is well-documented and widely supported in Arduino and embedded systems communities. It has a good measurement range, low power consumption, and comes in a compact breakout module. The BH1750 is especially useful in smart garden applications because it outputs data in a usable format (lux), which simplifies programming and decision-making within the system.

5. VEML7700 Ambient Light Sensor

The VEML7700 is an advanced digital light sensor that provides highly precise ambient light measurements in lux, with automatic gain control and a wide dynamic range. It also communicates over I2C and is capable of functioning in both low-light and full sunlight conditions. Its spectral response is close to human eye sensitivity, making it an excellent choice for applications where realistic brightness detection is needed. Libraries and example code are readily available, and its small footprint allows easy integration into compact designs. Its flexibility and superior performance make it one of the leading candidates in smart garden systems.

3.3.4 Mini Water Pump

In automated garden systems like GreenSync, the water pump plays a critical role in transporting water from a reservoir to the plant. Since the system is designed for compact environments like indoor gardens, balconies, or smart pots, the pump must be efficient, low-power, and easily controllable by a microcontroller such as the ESP32. There are several categories of mini pumps used in these kinds of systems, each offering different advantages in terms of flow rate, installation style, maintenance, and control. Below is an exploration of five common mini pump types suitable for small-scale irrigation or hydroponic setups.

1. Submersible DC Pump

One of the most commonly used pumps in small-scale watering systems is the submersible DC pump. These pumps, such as the JT-180A or RS-360 models,

are designed to be fully submerged in water and typically run on 3V to 12V DC power. Their popularity comes from their compact size, low noise operation, and reliable performance. They are easy to install, just drop them into a reservoir and they're readily compatible with microcontrollers using relay modules or transistor switches. Submersible pumps are ideal for low-lift watering tasks and work well in systems with basic tubing and gravity-fed layouts.

2. Peristaltic Pump

Peristaltic pumps offer a more precise way to control water flow. They operate by rotating rollers that compress flexible tubing, pushing water forward without allowing it to backflow. This mechanism ensures that only the tubing comes into contact with the water, which makes them great for systems that deliver nutrients or need to avoid contamination. These pumps are often used in dosing systems or nutrient delivery modules in hydroponics. Although they tend to have slower flow rates and can be more expensive than submersible pumps, they offer unmatched precision and cleanliness.

3. Diaphragm Pump

Miniature diaphragm pumps are another strong option. These pumps use a flexible membrane to draw in and expel water, creating suction and pressure through rapid back-and-forth movement. Many models can self-prime, meaning they don't need to be submerged or pre-filled with water to start working. They are also capable of handling slightly dirty or debris-filled water, which gives them an edge in less controlled environments. Diaphragm pumps are slightly bulkier than submersible ones but are durable and can push water over longer distances.

4. Centrifugal Pump

Centrifugal pumps operate using a spinning impeller to generate water flow. Though more commonly used in larger applications, there are brushless mini versions that can be integrated into compact systems. These pumps are typically not self-priming, which means they need to be submerged or filled before use. However, they excel at moving large volumes of water at low pressure, making them ideal for distributing water horizontally across plant beds or multiple zones. They are efficient in continuous-use situations but can require a bit more planning during installation.

5. Vibration Pump

Vibration pumps, also called electromagnetic pumps, move water using high-frequency oscillation. They are often used in ultra-compact gadgets and are favored for their small size and simplicity. These pumps generally offer lower flow rates compared to others and are better suited for systems where minimal water delivery is required. Their main advantage lies in energy efficiency and noise reduction, but their limited pumping power makes them less ideal for multi-plant or large-area irrigation systems.

3.3.5 Release Solenoid Valve

A critical element in automated watering systems is the release solenoid valve. This electromechanical device controls the flow of water through a system and is typically triggered by the microcontroller based on moisture sensor readings or scheduled commands. When selecting a solenoid valve for a smart garden setup like GreenSync, several factors must be considered, including voltage requirements, flow control mechanism (open/closed vs. proportional), physical size, and energy efficiency. While the basic function of all solenoid valves is to permit or block water flow, their internal designs and power handling methods can vary widely. Below are several commonly used solenoid valve types evaluated during our design process.

1. 12V Normally Closed Plastic Solenoid Valve

This is perhaps the most frequently used solenoid valve in small-scale irrigation systems due to its reliability and ease of integration. A normally closed (NC) valve stays closed by default and opens when a 12V DC current is applied. These valves are typically made of plastic components such as ABS or nylon, which offer good resistance to corrosion and wear in outdoor environments. The standard size (often with 1/2" or 3/4" hose threads) makes them compatible with most home plumbing or garden tubing setups. While they require a transistor or MOSFET circuit to control with a microcontroller like the ESP32, their widespread availability and consistent behavior make them an attractive option.

2. 5V Micro Solenoid Valve

Micro solenoid valves are designed for compact, low-flow applications. Operating at just 5V, these valves can be triggered more easily from logic-level circuits and are commonly seen in beverage dispensers or small hydroponic systems. Their small form factor makes them ideal for tight installations, such as vertical garden

panels or window-mounted plant boxes. Though they typically handle lower pressure and flow than larger 12V models, they are excellent for compact systems with small water reservoirs and limited power budgets.

3. Normally Open Solenoid Valve

Unlike the more common normally closed valve, a normally open (NO) valve allows water to flow freely until a signal is sent to close it. This configuration is beneficial in systems where passive or gravity-fed irrigation is used and where the goal is to stop watering only in certain conditions (e.g., soil oversaturation). While not widely used in basic DIY garden projects, NO valves can play an important role in fail-safe watering systems where power outages should not prevent the flow of water.

4. Latching Solenoid Valve (Bistable)

Latching solenoid valves, also known as bistable valves, consume power only during the switching process. They use a brief electric pulse to open or close and then remain in that state without continuous energy consumption. This makes them ideal for ultra-low-power applications, particularly battery- or solar-powered systems. However, they require additional circuitry, like an H-bridge, to reverse the polarity of the signal for toggling states. Despite this added complexity, they offer excellent energy savings in systems where frequent valve changes are unnecessary.

5. Proportional Solenoid Valve

Proportional solenoid valves allow for variable flow rates based on voltage level or PWM control, rather than simply toggling on and off. These valves are used in advanced irrigation or nutrient delivery systems where precision control is critical. While they offer high functionality, they are often more expensive and require more complex programming and signal handling. As such, they are not typically found in hobbyist or small garden projects, but their existence is important in showcasing the range of possibilities within smart irrigation technology.

3.3.6 Tubing

While it may seem like a minor element in an automated garden system, the choice of tubing has a noticeable impact on water flow consistency, system lifespan, and overall ease of installation. Tubing connects the water pump or solenoid valve to the plant area and ensures that moisture delivery is precise and

contained. For GreenSync, factors like diameter, material flexibility, pressure rating, and resistance to weather or algae buildup were considered when exploring tubing options. Below are three of the most common types evaluated for our system.

1. PVC (Polyvinyl Chloride) Tubing

PVC tubing is one of the most affordable and readily available types used in gardening and hydroponics. It's known for its good pressure tolerance, UV resistance, and compatibility with a wide range of fittings. Typically available in clear or opaque variants, PVC tubing is slightly more rigid than silicone but maintains enough flexibility for routing through garden setups. It's a strong choice when durability and cost are primary concerns. The downside is that it may become stiff in cold temperatures, which can make installation a bit more challenging in certain environments.

2. Silicone Tubing

Silicone tubing is prized for its flexibility and high-temperature resistance. In small-scale automated watering systems, its pliability makes it ideal for use with tight bends or intricate routing across plant beds or enclosures. It's especially helpful in compact systems where tubing must be threaded around components without kinking. However, it is generally more expensive than PVC and may not hold up as well to long-term UV exposure if used outdoors without shielding. For indoor systems or shaded greenhouses, though, silicone offers excellent ease of use and compatibility with low-pressure water delivery.

3. Vinyl Tubing (Clear Flexible Plastic)

Vinyl tubing occupies a middle ground between PVC and silicone. It's highly flexible and visually transparent, making it easy to monitor water flow or detect clogs. Vinyl is popular in DIY aquarium setups and small hydroponic systems for this reason. However, vinyl can harden or yellow over time, especially when exposed to direct sunlight or fluctuating temperatures. While not the most rugged option, it provides a clean, beginner-friendly solution for early prototypes or indoor systems where monitoring water flow is helpful.

3.3.7 Water Reservoir

The water reservoir plays a vital role in any automated irrigation system by serving as the central storage unit for all water that gets distributed to the plants.

While often overlooked, the design, material, and capacity of a reservoir directly affect water quality, flow consistency, and how often a user must refill the system. In GreenSync, the reservoir needed to be compact yet functional, with good resistance to algae growth and ease of integration with pumps and tubing. Below are three types of reservoir options that were considered.

1. Plastic Storage Containers (Custom or Repurposed)

One of the most flexible and cost-effective options for small garden systems is the use of standard plastic storage containers. These containers can be easily drilled to fit tubing and pump connections, are widely available in various sizes, and are typically made of food-grade plastic that is safe for water storage. However, they are not always opaque, which can lead to algae buildup if the container is exposed to light. Additionally, they may lack dedicated ports or mounting options, so some DIY effort is usually required to make them fit securely in a system.

2. Commercial Hydroponic Reservoirs

These are purpose-built containers designed specifically for hydroponic and irrigation setups. They often include pre-formed ports, lids to prevent evaporation, and dark-colored walls to reduce algae growth. Commercial reservoirs also tend to be made from UV-resistant plastics and come with measurement markers for water levels. While more expensive than repurposed containers, they save time in setup and offer features that are useful for long-term stability and maintenance. Their structured form also makes them easy to stack or position in modular systems.

3. Recycled or Upcycled Water Jugs / Containers

In a sustainability-minded design, some systems incorporate recycled water jugs, such as large plastic bottles or containers from household items like laundry detergent (thoroughly cleaned, of course). This option is appealing for its low cost and environmental friendliness. While these containers lack the durability or compatibility of commercial options, they are surprisingly effective in early-stage prototypes or ultra-low-budget builds. Care must be taken to ensure that the plastic is safe for water contact and that proper sealing is achieved around tubing or pump entry points.

3.3.8 🌞 LED Grow Light

When it comes to providing supplemental lighting for indoor plant systems like GreenSync, choosing the right grow light is crucial to maintaining healthy plant development. Since plants rely on specific wavelengths of light for processes like photosynthesis and photomorphogenesis, LED grow lights must be carefully selected based on spectrum, intensity, and control. Here, we explore five distinct types of LED grow light configurations that offer varying degrees of suitability for smart garden applications.

1. Full-Spectrum White LED Grow Lights

Full-spectrum white LEDs emit a balanced range of wavelengths that closely mimic natural sunlight. This makes them an excellent all-purpose lighting solution, capable of supporting plants through every growth stage, from seedling to harvest. These lights produce a more natural white light that is easier on the eyes for users and beneficial for aesthetic presentation in indoor environments. Their general compatibility and wide availability make them a practical option for compact systems like GreenSync. However, because they offer a wide, non-targeted spectrum, they may not be the most energy-efficient option for users who wish to optimize specific plant growth phases.

2. Red and Blue LED Arrays (Bi-Spectrum)

This type of grow light utilizes a targeted approach by focusing on the two wavelengths most crucial to plant growth — red (around 660 nm) and blue (around 450 nm). Blue light supports vegetative and leaf growth, while red light promotes flowering and fruiting. These bi-spectrum setups are common in lower-cost garden lighting kits and are highly power efficient due to their focused spectrum. However, their pinkish glow can be harsh in indoor settings and may not provide the balanced lighting needed for all plant types or stages.

3. COB (Chip-on-Board) LED Grow Lights

COB LEDs combine dozens of LED chips on a single substrate to create a compact, high-intensity light source. This design offers better light uniformity and deeper canopy penetration compared to traditional SMD (Surface Mounted Diode) arrays. For users needing strong lighting in a tight footprint, COB LEDs are a viable option, though they typically require active cooling or heat sinks due to the significant heat output. These lights are often used in commercial or more

advanced setups, but their inclusion is worth considering even in smaller systems if high light intensity is needed.

4. Adjustable Spectrum Grow Lights

Adjustable-spectrum LED lights offer flexibility by allowing users to manually or programmatically control the ratio of red, blue, and sometimes far-red or UV light. These lights are ideal for systems that grow a variety of plants with differing light needs or those that require tailored lighting schedules. For systems like GreenSync, this level of control could be integrated with a mobile app or pre-programmed routines, although such lights are typically more expensive and complex to operate. Still, their adaptability makes them a forward-thinking option for smart gardening systems.

5. LED Grow Light Strips

LED strips are a convenient and customizable lighting solution composed of small LEDs mounted on a flexible adhesive backing. These strips are available in both bi-spectrum and full-spectrum variants and can be easily installed around garden enclosures, under shelves, or inside grow boxes. They are particularly useful for even light distribution in tight spaces. While their light output may not be as strong as other solutions, their low profile, affordability, and flexibility make them a common choice for hobbyist and DIY garden setups.

3.3.9 MOSFET Relay Module / Transistor Switch

Transistor switches and relay modules play a critical role in enabling the ESP32 to control higher power components in the GreenSync system, such as the grow light, water pump, and solenoid valve. These modules essentially act as digital gates, allowing low-power control signals from the microcontroller to toggle larger current or voltage supplies safely and efficiently. Depending on the exact power demands of a component and the desired level of control or isolation, different switching technologies may be more appropriate. Below are three types of switches and relay systems commonly used in smart electronics projects.

1. N-Channel MOSFETs (e.g., IRF540N or IRLZ44N)

N-Channel MOSFETs are a staple in modern electronics due to their simplicity, efficiency, and speed. These transistors operate by applying a voltage to the gate, which allows current to flow between the drain and source terminals. When used in a switching configuration, they can effectively control devices drawing

several amps of current. Logic-level variants like the IRLZ44N are particularly well-suited for use with 3.3V logic systems like the ESP32, ensuring full gate activation without the need for additional drivers. These MOSFETs also support PWM control, making them ideal for applications like dimmable lighting or variable-speed motors. However, care must be taken to add flyback diodes when switching inductive loads like pumps or valves.

2. Prebuilt MOSFET Relay Modules

These relay modules are essentially plug-and-play boards designed for makers and microcontroller hobbyists. They often include onboard MOSFETs, optoisolators for electrical separation, and input/output terminals for easy integration. With support for standard logic signals and built-in protection components, they make it easy to control higher voltage devices like 12V water pumps or LED grow lights. Many also include status indicator LEDs that make debugging easier. These modules are a great choice for fast prototyping and offer a tidy, reliable way to switch loads without diving into discrete transistor circuit design.

3. Solid State Relays (SSR)

Solid State Relays offer a more industrial-grade solution for switching high-voltage or high-current devices. Instead of relying on mechanical movement like traditional relays, SSRs use internal optocouplers and MOSFET or triac arrays to achieve silent, rapid switching. Their electrical isolation between input and output enhances safety and makes them especially suitable for controlling AC-powered lights or pumps in greenhouse environments. Though more expensive and generally bulkier than MOSFET modules, SSRs provide exceptional reliability with no wear and tear over time. They're ideal for applications where long-term durability and minimal electrical interference are priorities.

3.3.10 📷 Camera

Selecting the right camera module is a crucial decision for any smart garden system like GreenSync, especially when the system relies on visual data for plant monitoring, growth tracking, or remote observation. While our goal is not to stream HD video or perform complex computer vision, the chosen module must strike a balance between resolution, power efficiency, integration simplicity, and

affordability. With a wide range of camera modules available—ranging from low-cost, low-res options to high-end imaging systems—it's important to explore viable solutions compatible with microcontrollers like the ESP32. Below are four strong candidates, each with distinct advantages and drawbacks, that we evaluated during our research.

1. OV2640 Camera Module

The OV2640 is a 2-megapixel sensor and arguably the most popular choice for ESP32-based camera projects. It offers multiple resolution modes up to UXGA (1600x1200) and includes onboard JPEG compression, which greatly reduces the load on the microcontroller's memory and processing. This sensor is directly compatible with the ESP32-CAM board, making it a plug-and-play option for many embedded applications. Despite its age, the OV2640 remains one of the most practical sensors due to its balance between image quality and processing simplicity. It's especially well-suited for systems that need occasional snapshots for remote plant monitoring, without overwhelming the microcontroller or Wi-Fi bandwidth.

2. OV7670 Camera Module

A legacy option that features VGA resolution (640x480), the OV7670 is valued for its low cost and basic image capturing capabilities. However, it lacks onboard compression and requires an external FIFO buffer for practical use with memory-constrained devices like the ESP32. Without that buffer, capturing images is unreliable and can cause system crashes due to RAM overflows. The OV7670 also uses an outdated parallel interface, making it more difficult to integrate in modern streamlined systems. Still, it holds a place in educational projects and budget builds where cost is the primary constraint and image quality is a secondary concern.

3. Arducam Mini (OV5642)

The Arducam Mini series steps up the game with higher resolution sensors like the OV5642, which supports image capture up to 5 megapixels. It includes onboard storage and JPEG compression, allowing it to offload heavy image processing from the microcontroller. The module connects over SPI, which is more manageable for the ESP32 compared to complex parallel interfaces. While more expensive than other options, Arducam Mini modules are better suited for applications that require detailed images, such as plant health diagnostics, or for

integration with machine learning-based plant classification systems. For GreenSync, it offers an excellent upgrade path if future expansion is considered.

4. ESP32-CAM

Though technically a bundled board rather than a camera alone, the ESP32-CAM module is a highly integrated and popular option in DIY smart garden builds. It combines an ESP32-S module with an OV2640 sensor, allowing it to operate as a standalone imaging device with Wi-Fi and camera capabilities. The board also includes support for a microSD card, onboard flash, and multiple I/O pins, making it a self-contained surveillance or monitoring unit. While it can overheat and lacks native USB support, it is widely supported by the community and fits neatly into compact enclosures. For GreenSync, this kind of integration is beneficial when modularity and cost reduction are priorities.

3.3.11 Storage

In any automated system like GreenSync, storing data effectively is an important consideration—whether for logging sensor readings, saving captured images, or keeping track of watering schedules and historical plant behavior. Storage solutions can vary depending on how much data needs to be saved, whether it should be removable, how long it needs to persist, and how accessible it should be to users or external applications. Below are several storage options that are commonly evaluated for embedded systems like ours, each with distinct benefits and limitations.

1. MicroSD Card

The microSD card is one of the most popular local storage solutions for microcontroller-based systems. It offers large capacities (up to hundreds of gigabytes), relatively fast write speeds, and the convenience of physical removability. For GreenSync, a microSD card could be used to store plant images from the onboard camera or maintain a local history of moisture readings and light levels. It requires a dedicated SPI interface and a bit of overhead in terms of programming, but it's an affordable and flexible option that aligns well with DIY and modular systems.

2. EEPROM (Internal or External)

EEPROM (Electrically Erasable Programmable Read-Only Memory) is great for storing small amounts of non-volatile data, such as calibration values, configuration settings, or the last known system state. Internal EEPROM is limited in space (often a few kilobytes), but external EEPROM chips can be added via I²C or SPI for slightly more capacity. Its key advantage lies in data persistence after power loss, but due to limited write endurance and capacity, it's not suited for bulk data logging or storing images.

3. External SPI Flash

This form of storage provides high-speed access and is often used for storing firmware or moderately sized data chunks. It's especially useful when the onboard flash of the ESP32 is not enough to hold everything needed, such as larger ML models or cached image data. While not removable like a microSD, it's typically faster and more reliable for repeated access. SPI flash chips are a good middle ground between EEPROM and SD cards in terms of cost, speed, and complexity.

4. Mobile App Storage (Remote via BLE/Wi-Fi)

In modern systems like GreenSync, offloading data to a companion mobile app is an attractive and convenient approach. Using Wi-Fi or Bluetooth Low Energy (BLE), the ESP32 can wirelessly transmit sensor data, images, or status logs to a smartphone app. This enables not only local storage on the phone, but also real-time display, analysis, and even cloud backup through app-side integrations. It eliminates the need for physical storage on the embedded device and aligns perfectly with user-friendly interfaces and long-term accessibility.

5. FRAM (Ferroelectric RAM)

FRAM combines the best of both worlds—non-volatility and high-speed read/write performance. Unlike EEPROM, FRAM has virtually unlimited write cycles and doesn't require high voltage for writing. It's well-suited for frequent data logging, such as rapid sensor polling or system diagnostics. However, its cost and relatively low storage capacity (usually under 1MB) limit its use to specialized tasks. In GreenSync, FRAM might be considered if extremely robust, battery-free logging is needed in future versions of the system.

3.4 Supplementary Design Systems

3.4.1 Custom PCB Design Software

1. KiCad

KiCad is a free, open-source PCB design suite widely recognized for its flexibility and professional-grade capabilities. It supports schematic capture, multi-layer PCB layout, and even 3D visualization of boards. KiCad is highly popular in academic and open-source communities due to its cost-free model and extensive library support, making it an excellent choice for student and hobbyist projects.

2. EasyEDA

EasyEDA is a browser-based design tool that simplifies PCB development by integrating design, simulation, and ordering services into one platform. With its intuitive interface and direct connection to manufacturers like JLCPCB, it reduces production turnaround time significantly. Its web-based nature also allows for easy collaboration, making it popular among small teams.

3. Altium Designer

Altium Designer is considered the industry gold standard for PCB design. It offers advanced routing algorithms, real-time design rule checks, and multi-board integration, which are ideal for complex, large-scale projects. However, its high licensing cost and steep learning curve make it less suitable for student or hobbyist projects but an excellent benchmark in terms of functionality.

4. Autodesk Fusion 360 (Electronics)

Fusion 360 integrates mechanical and electronic design workflows, making it perfect for projects requiring precise enclosure and PCB alignment. The electronics module allows for schematic design and PCB layout while maintaining seamless integration with 3D modeling. This makes Fusion 360 particularly valuable for GreenSync, where the PCB must fit tightly within a custom enclosure.

5. EAGLE (by Autodesk)

EAGLE remains a strong choice for small to medium PCB projects, offering a balance of ease-of-use and powerful features. It supports schematic capture and PCB layout with extensive component libraries. While Autodesk has shifted its focus to Fusion 360, EAGLE is still widely supported and popular among hobbyists and educational users.

6. Proteus

Proteus stands out for combining PCB design with simulation capabilities. Users can simulate circuits in real time before committing to fabrication, which minimizes errors and development costs. While its PCB design features are less advanced than Altium or Fusion, the integrated simulation environment makes it a valuable tool for academic projects and rapid prototyping.

3.4.2 Power Supply

Powering an automated system like GreenSync requires a dependable and efficient energy source capable of supporting sensors, actuators, and wireless communication modules. The choice of power source affects the overall portability, scalability, and reliability of the system. Below are several common power supply options considered for projects of this type:

1. Wall Adapter (DC Power Supply)

Wall adapters are among the most reliable and widely used solutions for stationary embedded systems. They convert AC mains voltage into a stable DC output (typically 5V or 12V) suitable for powering microcontrollers and peripherals. This method ensures uninterrupted operation as long as the system remains plugged in, making it ideal for indoor environments where mobility is not a concern.

2. Rechargeable Li-Ion / Li-Po Battery Pack

Rechargeable lithium-ion and lithium-polymer battery packs offer excellent energy density and are commonly used in portable devices. For a project like GreenSync, these batteries can provide backup power during outages or enable temporary wireless operation. However, they require charging circuits, protection modules, and voltage regulation to ensure safe operation.

3. AA Battery Pack (Alkaline or NiMH)

AA batteries remain a simple and low-cost power source for low-current applications. They are easy to source and replace, making them attractive for small-scale or educational projects. However, their limited capacity and inability to sustain high-load components like pumps or grow lights for long periods make them less practical for continuous operation.

4. USB Power Source

Using USB as a power supply is common during prototyping because of its

convenience and compatibility with microcontrollers like the ESP32. While USB provides a stable 5V output, its current limitations (typically up to 500mA on standard ports) can restrict powering additional hardware such as water pumps or LED grow lights.

5. Solar Panel (with Battery Storage)

Solar power offers an eco-friendly and off-grid solution for plant care systems, especially for outdoor setups. When paired with an energy storage system like a rechargeable battery and a charge controller, solar panels can maintain continuous operation without reliance on grid electricity. However, their complexity and dependence on weather conditions make them better suited as an advanced feature rather than a core power source.

3.4.3 Voltage Regulation Modules

Maintaining a stable voltage supply is crucial for the proper operation of embedded systems, as fluctuations can cause erratic behavior or damage sensitive components. For a system like GreenSync, which includes sensors, actuators, and wireless communication modules, voltage regulation ensures consistent performance and safety. Below are three commonly used voltage regulation methods considered for this design:

1. Linear Regulators (e.g., LM7805, AMS1117)

Linear voltage regulators are among the simplest and most cost-effective solutions for stepping down voltage to a fixed level, such as 5V or 3.3V. They operate by dissipating excess energy as heat, which makes them inherently less efficient—particularly when the input voltage is significantly higher than the output. While ideal for low-power circuits due to their low noise and ease of use, they are unsuitable for high-current loads like pumps or grow lights because of their energy loss and thermal issues.

2. Buck Converter (Step-Down Switching Regulator)

Buck converters provide a far more efficient alternative for voltage regulation by using a high-frequency switching mechanism rather than dissipating excess energy as heat. This makes them ideal for components that draw higher currents, such as water pumps or LED grow lights, ensuring minimal power loss and better thermal performance. Although slightly more complex than linear regulators, their efficiency makes them well-suited for GreenSync's power-hungry peripherals.

3. Buck-Boost Converter

Buck-boost converters offer the most versatility by supporting both step-up and step-down voltage regulation. This is particularly valuable in systems powered by batteries, such as Li-Po cells, where voltage can fluctuate below or above the required operating voltage. By maintaining a stable output regardless of input variations, buck-boost converters enable consistent performance across a wide range of scenarios. However, their complexity and higher cost compared to simpler regulators may limit their use to advanced or portable configurations.

3.4.4 Software Development Environment

Developing reliable firmware for the ESP32 microcontroller is a key part of GreenSync's functionality. The choice of development platform affects ease of coding, debugging efficiency, and access to hardware-specific libraries. Several platforms are available, each offering distinct benefits depending on project complexity and user experience level.

1. Arduino IDE

The Arduino IDE remains one of the most popular environments for programming ESP32 boards due to its simplicity and extensive community support. It provides an easy-to-use interface, a large ecosystem of pre-built libraries, and a straightforward workflow for uploading code to the microcontroller. While it lacks some of the advanced debugging tools and granular control found in other platforms, its accessibility makes it ideal for rapid prototyping and educational use.

2. ESP-IDF (Espressif IoT Development Framework)

ESP-IDF is the official development framework provided by Espressif for ESP32 microcontrollers. Unlike the Arduino IDE, ESP-IDF offers low-level access to hardware features and includes advanced capabilities such as FreeRTOS support for multitasking. It is designed for developers who require fine-grained control and optimized performance. However, the increased complexity and steeper learning curve make it more suitable for experienced programmers or projects with advanced requirements.

3. PlatformIO

PlatformIO is a modern, cross-platform development environment that integrates seamlessly with popular editors such as Visual Studio Code. It supports multiple frameworks, including Arduino and ESP-IDF, allowing developers to choose the best tool for their workflow. PlatformIO also features automated library

management, debugging tools, and easy integration with version control systems like Git. These capabilities make it a flexible and scalable option for teams working on sophisticated IoT projects.

3.4.5 Interface

An effective user interface is critical for monitoring system performance and interacting with GreenSync's features. The interface must be intuitive, responsive, and accessible across different user scenarios. For this reason, three main interface approaches were considered:

1. Mobile Application (Android or Cross-Platform)

A mobile app provides the most user-friendly and versatile interface for GreenSync. It allows plant owners to monitor soil moisture, light exposure, and watering events remotely. Features such as time-lapse photo viewing, care recommendations, and manual override controls can be integrated for a seamless experience. Using a cross-platform framework like Flutter or a native Android app ensures broad device compatibility and the potential for push notifications.

2. Onboard LCD Display

Including a small onboard display offers immediate, at-a-glance access to essential plant data without needing a smartphone. Displays like OLED panels or standard LCD modules can show real-time metrics such as moisture percentage and light intensity. This solution adds redundancy in case of mobile app issues and caters to users who prefer physical interfaces for quick checks.

3. Web-Based Dashboard (Web Server)

A web-based dashboard enables users to access system data through any browser, eliminating the need for dedicated app installations. This interface is hosted on the ESP32 itself, leveraging its Wi-Fi capability to serve a lightweight web page that displays sensor readings and allows basic control functions. The main advantage of this approach is universal compatibility and easy updates without requiring mobile app maintenance.

3.4.6 Enclosure and Housing Design

The enclosure plays a critical role in protecting electronic components from environmental factors while maintaining functionality and aesthetics. A well-designed housing ensures proper airflow, cable management, and durability,

while also complementing the overall look of the GreenSync system. Below are five enclosure options considered for this project:

1. 3D-Printed Enclosure (PLA/ABS)

3D printing provides a fully customizable solution that can be designed to fit the exact dimensions of the PCB, sensors, and other hardware. Using materials like PLA or ABS, the enclosure can be tailored with precise cutouts for ports, buttons, and displays. This approach offers flexibility for iterative design changes and is ideal for prototyping or final builds that require a compact, polished appearance.

2. Acrylic or Polycarbonate Panels

Transparent acrylic or polycarbonate sheets can be assembled into an enclosure that highlights the internal components, making it visually appealing for demonstrations or educational purposes. These materials are lightweight, easy to clean, and provide a modern look. However, they require precision cutting and may be less durable under impact compared to other materials.

3. Pre-Fabricated Project Box (ABS or Metal)

Off-the-shelf project enclosures provide a cost-effective and durable solution for housing electronics. Available in various sizes and materials, these boxes offer robust protection and are often designed with mounting points for PCBs. While they reduce design time, they typically require manual modifications like drilling holes for sensors, connectors, or ventilation.

4. Wooden Casing

A wooden enclosure offers an eco-friendly and aesthetically pleasing alternative for indoor setups. Its natural look complements home décor and adds a unique touch to the system. However, wood is sensitive to humidity and temperature changes, making it less suitable for environments with fluctuating conditions.

5. Metal (Aluminum) Enclosure

Metal housings, particularly aluminum, provide superior durability and excellent heat dissipation, which is beneficial for components that generate heat. These enclosures are ideal for rugged environments or advanced setups requiring strong protection. The downside is the increased weight and the need for specialized tools to create precise openings for components.

3.4.7 Soil Type Considerations

Soil composition plays a critical role in how plants absorb water, retain nutrients, and exchange air. For automated systems like GreenSync, understanding soil properties is essential to ensure accurate sensor readings and proper watering logic. Moisture sensors behave differently in soils with varying textures and densities, and improper pairing of soil type and irrigation strategy can lead to under- or overwatering. Below are five common soil types considered for indoor plant setups:

1. All-Purpose Potting Mix

This is the most widely used soil type for houseplants, offering a balanced combination of nutrients, drainage, and aeration. It is lightweight and designed specifically for potted environments, making it an excellent baseline for moisture sensing. Potting mix generally contains peat moss, perlite, and composted materials, providing consistency that works well with automated watering systems.

2. Garden Soil

Garden soil, while nutrient-rich, is often too dense for container gardening and can create drainage problems when used indoors. Its tendency to compact over time can hinder root growth and cause moisture retention to vary unpredictably. For automated systems, this inconsistency poses challenges for moisture sensors, which rely on stable soil conditions to provide accurate readings.

3. Succulent and Cactus Mix

Succulent and cactus soils are formulated for excellent drainage, incorporating coarse sand and perlite to minimize water retention. These mixes are ideal for drought-tolerant plants but require adjustments in watering frequency when using automated systems. Moisture sensors placed in this type of soil will detect rapid drying, so calibration and threshold settings must reflect the soil's fast-draining nature.

4. Peat-Based Mix

Peat-based mixes are commonly found in commercial potting blends because they are lightweight and hold water well. While beneficial for moisture-loving plants, their high water retention can make overwatering a risk in automated setups. Additionally, peat's environmental impact has prompted interest in alternatives, but its use remains widespread in indoor gardening.

5. Coco Coir Mix

Coco coir is a sustainable alternative to peat moss that offers excellent water

retention and aeration. Its fibrous structure prevents compaction, making it ideal for container plants and compatible with sensor-based irrigation. Because coco coir releases water gradually, it pairs well with automated systems designed to maintain consistent soil moisture levels over time.

Chapter 4 Standards and Design Constraints

4.1 Standards

4.1.1 Safety and Health Concerns

There will be no methods, equipment, or techniques that involve extremely hazardous chemicals that will be dealt with in this project. The wiring between components, on the other hand, is a clear area of concern with regard to safety. This includes the connection between the AC to DC converter, the connection between the AC to DC converter and the water pump, the connection between the AC to DC converter and the LED light strips, and any other connection that is responsible for the transfer of current between wired components.

When it comes to preventing electrical risks like short circuits, overheating, or inadvertent exposure to live wires, proper insulation and secure connections are very necessary. In addition, strain relief measures must be put into place in order to guarantee that wires are not pulled or detached by accident when the system is functioning normally. Protecting components from the possibility of overcurrent circumstances can be accomplished by the incorporation of fuses or circuit breakers, which can further increase safety. In spite of the fact that the system runs at relatively low DC voltages after conversion, the original AC input still offers a potential risk. Because of this, it is vital for the system to be handled carefully and for electrical components to be enclosed appropriately in order to ensure safe operation.

4.1.1.1 Adherence to the Standards Established for Health and Safety

A wide range of distinct safety requirements have been observed and adhered to during the course of this project. Particularly with regard to the wiring of the water pump, the International Electrotechnical Commission (IEC) 60335-2-51: stationary circulation pumps for heating and service water installations and IEC 60335-2-55: electrical appliances for use with aquariums and garden ponds will be adhered to in a meticulous manner. This is especially true with regard to the restrictions on the bending of the wiring near the wall outlet. In addition, all plug connections will be made in line with the plug standards established by the National Electrical Manufacturers Association (NEMA), specifically NEMA 5-15. This is done to guarantee that the plug that is used for any given current carrying application is of the proper size. When it comes to the pressure ratings of the pipes and tubing, the American Society for Testing and Materials (ASTM) requirements that are mentioned in ASTM D1785 are strictly adhered to for the 1/4" schedule 40 PVC pipe that is being utilized for the water system.

4.1.1.2 The Electrical Safety Standards

The dependability, user safety, and durability of the [name of our project] system are all greatly impacted by the electrical safety regulations that are in place. IEC 60529 provides a description of ingress protection (IP) ratings, which enable outdoor devices to be protected against elements such as water, dust, insects, and plant debris that are typically found in garden settings. In order to reduce the likelihood of hazards like electric shocks and fires, the National Electrical Code (NFPA 70) is strictly adhered to while planning wiring. ISO 50001 encourages the effective control of energy consumption, which is especially advantageous given that the system makes use of renewable energy sources such as solar and battery power.

4.1.1.3 Standards for the Design of PCBs

Standardization of the design of printed circuit boards (PCBs) establishes the criteria that must be met in order to guarantee that a PCB can be properly manufactured and functionally utilized as intended. Frequently, the producer will

specify certain criteria for the product. As was indicated before, the manufacturer that has been chosen for this project is JLCPCB. The design process will be guided by their specific criteria, and the specific standard that will be employed in relation to the PCB design will be different for each firm.

For instance:

- The holes that are drilled in the printed circuit board (PCB) should have a range of 0.3 mm to 6.3 mm, with the minimum size of the via holes being 0.3 mm and the pad diameter being 0.5 mm.
- Vias are required to be positioned at a minimum distance of 0.254 millimeters from other vias and traces, regardless of whether or not they are net.
- A minimum clearance of 0.3 millimeters is needed between any trace and the edge of the board.
- The lowest permitted trace width is 0.127 millimeters, and traces must maintain a spacing of 0.127 millimeters from one another.
- When it comes to 2-layer boards, the options for the thickness of the outer copper layer are restricted to either 1 ounce or 2 ounces.
- The minimum spacing requirements for different nets include a distance of 0.5 millimeters between the holes and pads.
- It is recommended that pads have a minimum clearance of 0.127 millimeters from pads on different nets, and only 0.2 millimeters from traces.

4.1.1.3.1 PCB Standard IPC-2221

For the purpose of creating printed circuit boards that are long-lasting, functional, and acceptable for manufacturing, the IPC-2221 standard acts as a basic guideline. It covers a wide variety of subjects with the goal of improving the performance of printed circuit boards (PCBs) as well as their dependability. In the standard, the following important aspects are brought to the forefront:

1. Management of the Temperature:

For the purpose of preventing component failure and ensuring long-term dependability, thermal management is necessary. Effective heat dissipation is particularly important. In order to effectively regulate temperature distribution, the International Power Control (IPC) 2221 gives suggestions about the utilization of thermal vias, the selection of suitable board materials, and the positioning of heat-generating components.

Design for the purpose of manufacturing:

The International Product Standards (IPC) 2221 places an emphasis on simplifying the manufacturing process by making design decisions that improve fabrication, assembly, and testing practices. During the production process, adhering to DFM procedures helps decrease costs, boost yield, and eliminate mistakes.

2. *Routing of Traces:*

The standard provides comprehensive instructions for planning the arrangement of traces, with a particular emphasis on maintaining signal integrity, controlling impedance, and reducing electromagnetic interference (EMI). It provides procedures for the routing of high-speed communications in order to lessen the effects of crosstalk and signal degradation.

Placement of Components:

An appropriate arrangement of components improves both the electrical performance and the thermal balance of a system while simultaneously simplifying assembly. Through the use of strategic layout, the standard provides instructions on how to prevent interference, improve access for testing, and increase the dependability of the system.

The Selection of Materials:

IPC-2221 specifies criteria for selecting board materials based on thermal conductivity, dielectric constant, and mechanical robustness. These criteria are used to select materials for boards. The selection of the

material has a direct influence on the quality of the signal transmission and the resilience to external stress.

3. *Guidelines for the Design:*

Among the fundamental factors that are defined by the standard are the minimum trace width, clearance, and layer stack-up criteria. The presence of these guarantees that the board is able to meet power needs, prevent short circuits, and keep its general functioning intact.

4. *Reliability and Quality:*

IPC-2221 offers suggestions for inspection techniques, testing protocols, and quality assurance processes that help uncover faults and certify conformity with industry benchmarks. These recommendations are included at the conclusion of the document to guarantee that consistent performance is achieved.

5. *Considerations Regarding the Environment:*

As an additional recommendation, IPC-2221 advocates design techniques that take into account the operating context and the influence on the environment. This involves making certain that the material is compatible with severe circumstances such as fluctuations in temperature and humidity, as well as vibrations caused by mechanical motion. When environmental resilience is taken into consideration throughout the design process, it results in longer product life cycles and lower failure rates in the field.

6. *The integration of electromechanical systems:*

Through the detailing of mechanical limitations, such as mounting hole location, board outline tolerances, and connection alignment, the standard provides assistance for integration with mechanical components and housings. By ensuring that the printed circuit board (PCB) fits seamlessly into enclosures and interacts appropriately with other system parts, proper electromechanical design strengthens the overall resilience of the system and makes it more compatible with assembly.

These ideas are included into IPC-2221, which acts as a sturdy foundation for the creation of high-performance printed circuit boards (PCBs) that are capable of meeting the stringent criteria of current electronic systems. Our design will be guided by this standard, which, when paired with the limits that are specific to the manufacturer, will assure quality, efficiency, and the ability to be manufactured. These factors that are taken into account within the standard are summarized in the table that follows:

Table: List of Categories and Descriptions for the IPC-2221 Specification

Classifications of the Standard Specifications	Description
Management of the Temperature	Thermal vias and layout approaches are recommended to reduce overheating and maintain long-term dependability.
Design for the purpose of manufacturing	Promotes layout methods that ease fabrication, assembly, and testing, reducing mistakes and manufacturing costs.
Routeing of Traces	Facilitates layout methods that ease fabrication, assembly, and testing, reducing mistakes and manufacturing costs.
Placement of Components	Specifies signal integrity, EMI mitigation, and impedance control for high-speed signal routes.
The Selection of Materials	Improves signal flow, thermal performance, and testing and assembly accessibility by guiding part location.
Guidelines for the Design	Choose materials based on electrical, thermal, and mechanical qualities for performance and environmental demands.

Reliability and Quality	Supports power and signal needs by defining fundamental PCB features such trace width, spacing, and layer configuration.
Considerations Regarding the Environment	Specifies inspection and testing methods to assure board durability and performance.
The integration of electromechanical systems	Ensures system-level integration by recommending board fit, mounting holes, and interface alignment.

4.1.1.4 Standards for Wireless Communication and Connectivity

The successful operation of the [name of our project]. system is contingent upon the components, which include soil moisture sensors, microcontroller units (MCUs), actuators, and the user interface on a mobile application, communicating with one another in a seamless manner. The compliance with wireless communication standards guarantees the dependability and responsiveness of this contact. Bluetooth Low Energy (BLE) is employed for communication that is both short-range and energy-efficient, notably between sensors and the modular computer unit (MCU). Real-time data monitoring and system control are made possible by the implementation of IEEE 802.11 (Wi-Fi), which allows for high-speed and robust connectivity to and from the cloud or mobile application environments. Furthermore, the MQTT protocol, which is standardized under ISO/IEC 20922, facilitates the transfer of data between devices and the cloud in a lightweight and efficient manner, which is very important for Internet of Things-based gardening systems. The use of these standards guarantees the establishment of a communication system that is not only quick and scalable, but also strong enough to manage a variety of smart gardening activities, including logging, automation, and real-time notifications.

4.1.1.4.1 Wireless Comm Standard IEEE 802.11

In the context of this project, wireless communication is an essential component since it enables the exchange of data between the system and electronic

equipment that are external to it. This communication is made possible by the IEEE 802.11 standard, which provides a set of protocols that enable compatibility across a range of wireless devices. This standard is crucial in making this communication possible. By defining fundamental characteristics like as frequency ranges, modulation methods, and data transmission protocols, this standard sets the platform for devices to share data in a unified manner. It does this by laying the foundation for the technology.

The specification of frequency bands that are utilized for communication is one of the most important aspects of the IEEE 802.11 standard. The bands operating at 2.4GHz and 5GHz are two of the most frequently utilized frequencies. The 2.4GHz band is particularly useful since it provides a larger range and better penetration through barriers such as walls. As a result, it is perfect for usage in contexts such as the house and interior spaces, where devices may need to communicate over longer distances. On the other hand, the 5GHz band is capable of supporting quicker data transmission speeds; however, its range is more restricted, and it has a greater difficulty dealing with obstructions than the 2.4GHz band does. The standardization of these frequency bands makes it possible for devices to quickly identify and tune into the right frequency, hence reducing the amount of interference that is caused by other devices that carry out their operations on other frequencies.

The IEEE 802.11 standard also features sophisticated data transmission techniques, such as Orthogonal Frequency Division Multiplexing (OFDM), which splits the data into numerous smaller streams in order to optimize the speed at which it can be transferred. In addition, Direct Sequence Spread Spectrum (DSSS) is utilized in order to broaden the bandwidth and decrease interference. Wireless communication is needed for reliable data transfer in dynamic contexts, and these technologies increase the robustness and efficiency of wireless communication, which is crucial for achieving this.

There are several variants of the IEEE 802.11 family, each of which offers a unique set of benefits that are determined by the requirements of the application. For this particular project, the microcontroller that has been chosen is the ESP32, which is capable of supporting 802.11b, 802.11g, and 802.11n. 11 megabits per second is the maximum speed that can be achieved with the 802.11b version, which works on the 2.4GHz band. In spite of the fact that it is adequate for

fundamental data transmission tasks such as streaming video, it is much slower than previous versions. Despite the fact that it operates on the 2.4GHz range, the 802.11g standard incorporates OFDM, which allows it to achieve data speeds of up to 54 megabits per second. As a result of this enhancement, the video quality may be improved, and the data transfer can be accelerated, providing a satisfactory balance between speed and range.

It is possible to use the 802.11n version for applications that require greater speeds since it runs over both the 2.4GHz and 5GHz bands. This provides flexibility in terms of both coverage and speed. Within the context of this project, the ESP32 makes use of the 2.4GHz band of the 802.11n standard, which is capable of achieving rates of up to 150 megabits per second. Due to the fact that it guarantees efficient communication between the moisture sensor boards, the main processing unit, and the associated mobile app, this is more than sufficient for the requirements of this project.

Incorporating IEEE 802.11 assures interoperability with a wide variety of devices and provides a smooth integration into networks that are already in place. Due to the fact that it adheres to a well-established standard, it ensures that communication is both efficient and dependable, making it an absolutely perfect option for this project. Furthermore, it simplifies the work of ensuring that both the data supplied from the sensor devices and the data received by the system are both comprehensible and interoperable, which makes it easier for users to interact with the final product in a fluid manner.

4.1.1.4.2 ESP-NOW Wireless Communication

At Espressif Systems, the company that is responsible for the widely used ESP32 and ESP8266 microcontroller families, a unique wireless communication protocol known as ESP-NOW was developed. Direct device-to-device data transfer is made possible by ESP-NOW, which does not require the use of a conventional Wi-Fi network or router. This was designed to be an efficient, low-power, peer-to-peer communication method. It is the intention of this project to make use of this communication protocol in order to transmit the moisture sensing data from an ESP32 that is collecting the data to an ESP32 that is located in the central location. This protocol has become an essential component

of Espressif's wireless stack, particularly for situations that call for low-latency communication and minimal infrastructure.

The 2.4 GHz ISM band is the same unlicensed frequency range that Wi-Fi and Bluetooth technologies employ. This is where ESP-NOW's main functionality is located. Wi-Fi, on the other hand, is dependent on the IEEE 802.11 association mechanism, but ESP-NOW does not. For the purpose of exchanging data between devices, it employs a simplified form of 802.11 frame transmission, which enables communication that is both quick and lightweight. Without the overhead that is generally associated with Wi-Fi authentication and IP-based protocols, devices that use ESP-NOW are able to transmit and receive messages in a manner that was nearly immediate. It is specifically quicker than other transmission techniques because ESP-NOW lowers the five levels of the OSI layer model to just the data connection and physical layers. This is the case since ESP-NOW is a specific reduction.

A broadcast and peer-to-peer communication paradigm is utilized by ESP-NOW, which sets it apart from other similar systems. The MAC address of each device, which is referred to as a peer, is used to identify the device. When using ESP32 devices, communication can take place between as many as twenty peers. Although it is not necessary for these peers to be linked to a Wi-Fi network, it is possible for ESP-NOW and Wi-Fi to coexist on the same chip, which enables hybrid use cases to be implemented. Those applications that require many embedded devices to synchronize or exchange data without requiring internet connectivity or a centralized server are ideal candidates for the protocol since it is well-suited for those applications.

With the use of the 802.11 Action frame subtype, ESP-NOW is able to send data in either encrypted or unencrypted formats, depending on the specific technological requirements. As a result of the payload size being restricted to 250 bytes per message, it is more appropriate for relatively brief bursts of data than for communication that requires a large bandwidth. Naturally, for the purpose of this project, the data pertaining to moisture sensing can be readily wrapped in just a single byte. Therefore, 250 is more than plenty to communicate the data, and size is not at all a worry in this particular scenario. This packet format offers a reasonable compromise between complexity and performance, making it suitable for applications that require low-latency and predictable

behavior. Some examples of such applications are sensor networks, device orchestration, and basic automation and control systems.

ESP-NOW is a protocol stack and operating model that is significantly different from Wi-Fi and Bluetooth, despite the fact that it operates on the same frequency range as both of these technologies. The ESP-NOW protocol, in contrast to Bluetooth, provides a greater range and quicker transfer rates without the need for any pairing or discovery processes to be carried out. The fact that ESP-NOW significantly reduces the amount of time required for the devices to handshake during the Bluetooth pairing process makes this a particularly crucial point to keep in mind. The ESP-NOW protocol, in contrast to the Zigbee protocol, does not rely on a mesh network architecture and does not require a coordinator or gateway. The differences between the two protocols underscore its particular function as a lightweight, rapid-deployment protocol that is best suited for contexts that require point-to-point or small-group communication without requiring a significant amount of network overhead.

ESP-NOW's status as a proprietary product is a significant source of differentiation for the company. It is not a standard that is under the control of a formal standards body like the IEEE or the Bluetooth Special Interest Group (SIG). As an alternative, Espressif Systems is responsible for its whole development, maintenance, and support. While this does make it possible for Espressif to have a deep integration with its own hardware platforms, it also means that ESP-NOW is not generally compatible with microcontrollers or chips that are manufactured by other companies. It is beyond the range of official industry standards due to the fact that ESP-NOW is a proprietary product, despite the fact that it plays a significant role within the ecosystem of ESP-NOW development.

Even though it has some limits that are unique, ESP-NOW is in compliance with the basic regulatory criteria that are imposed on devices that operate in the 2.4 GHz ISM band. In the United States, it is governed by the Federal Communications Commission (FCC), and in Europe, it is governed by the European Telecommunications Standards Institute (ETSI). In a manner analogous to that of Wi-Fi and Bluetooth devices, this means that devices that utilize ESP-NOW may be deployed in the majority of locations without the need for specialist licensing. With that being said, its utilization is inextricably linked to

Espressif hardware, which limits its usability in more generalized scenarios that involve several vendors.

As a conclusion, ESP-NOW is a wireless communication protocol that is very effective yet proprietary. It was built to suit certain needs for performance and implementation. By providing ultra-lightweight peer-to-peer communication with little latency and low power consumption, it makes a significant contribution to the wireless landscape and fulfills a function that is unique to it. Despite the fact that it is not a formal standard, it reflects Espressif's strategic ambition to deliver powerful communication capabilities that are designed for embedded applications within its hardware platform. Because of this, ESP-NOW is best understood as a communication protocol that was created specifically for a specific purpose, rather than as a general-purpose industry standard.

4.1.1.5 Standards for Data Security and Privacy

In light of the fact that smart gardening systems capture, transmit, and retain sensitive data—including environmental conditions, watering schedules, and user preferences—it is essential to have data security and privacy guidelines in place. The International Organization for Standardization (ISO) 27001 offers a framework for managing information security. This framework ensures that the data that is gathered is encrypted, kept securely, and safeguarded against unwanted access. This is of utmost significance in situations when the system links to cloud platforms or mobile apps respectively. Furthermore, the National Institute of Standards and Technology Cybersecurity Framework for the Internet of Things provides actionable information to improve the security of devices. This guidance covers topics such as secure firmware upgrades, authentication mechanisms, and network safeguards. In addition to safeguarding user information, the [name of our project] system also fosters trust and resiliency within the smart gardening experience. This is accomplished through the implementation of these standards.

4.1.1.6 Standards for Smart Lighting Components

When it comes to fostering the growth of plants and preserving the equilibrium of the environment, smart lighting is an essential component, particularly in places that are shaded or indoor gardens. The system adheres to the International

Electrotechnical Commission (IEC) 60598, which specifies the standards for the safe functioning of lighting fixtures that are designed to withstand the elements and are used in outdoor settings. This guarantees that the lights are able to withstand different temperatures, as well as exposure to UV radiation and moisture. Light sensors and controllers that are created in accordance with ISO 9241-303 are utilized by the system in order to achieve optimal energy utilization and real-time responsiveness. These controllers and sensors are responsible for guiding the performance of visual displays and ensuring precise brightness adjustment based on their surroundings. Observing these lighting standards encourages the development of healthy plants, cuts down on the use of energy that is not essential, and guarantees that the system will be able to function in a secure and dependable manner throughout the course of time.

4.1.1.7 Standards for Sustainability and Energy Efficiency

Energy efficiency criteria are the driving force behind the [name of our project] system's environmentally responsible functioning, which is centered on the concept of sustainability. The capacity of the system to monitor and minimize energy usage across all key components, including pumps, sensors, and lighting systems, is supported by ISO 50001. This helps to ensure that power is utilized and consumed in an efficient manner. Solar power or hardware that is efficient in terms of energy consumption can be included into the system to lessen its reliance on external energy sources. Furthermore, the EPA WaterSense recommendations, which encourage the use of water-saving technology to limit waste while supporting healthy plant development, may be aligned with irrigation efficiency in order to enhance irrigation efficiency. A gardening solution that is both environmentally sensitive and cost-effective is promoted by these standards collectively. This solution reduces the amount of resources that are consumed without affecting the performance of the garden.

4.1.1.8 Standards for Sensors and the Environment

To ensure the success of any intelligent gardening system, it is essential to exercise precision and accuracy when monitoring the surrounding environment. For the purpose of ensuring the gathering of accurate data from soil, water, air, and light conditions, the [name of our project] system adheres to environmental and sensor standards. Both ISO 18400 and ISO 11074 are standards that specify

procedures for evaluating and monitoring soil quality. These methodologies provide direction for the positioning and calibration of sensors that measure moisture, pH, and nutrients. In order to provide intelligent irrigation scheduling, ISO 772 assures that water flow rates and efficiency are measured in a consistent manner. This is helpful for monitoring water use. Components of air quality, such as temperature and carbon monoxide sensors, contribute to the maintenance of a consistent microclimate, which is essential for the development of plants. Through adherence to these criteria, the [name of our project] system is able to provide precise data on the environment, which in turn enables intelligent automation and contributes to the development of a more robust garden ecosystem.

4.2 Constraints

4.2.1 Constraints of Sustainability

4.2.1.1 Battery Longevity

This project has a number of significant restrictions, one of the most significant of which being environmental impact caused by powered gadgets. Because the objective of this project is to provide the user with hands-off automation as soon as the project is handed over to them, it is very undesirable for the design to require the replacement of power supplies such as batteries. For this reason, the objective was to avoid utilizing batteries wherever it was practicable and reasonable to do so in the design. This was accomplished by extracting 120V AC power from the wall. The water pump was one instance in which this point was brought up. As an illustration, the device might be simply powered by attaching it to a 12V lead acid battery. This would be applicable to any water pump that operates at 12V. However, despite the fact that this is a workable solution, the battery will ultimately lose its charge over the course of time, and if this happens, there are many limits that might become an issue. As a first and foremost matter, the fact that the pump battery is dying and there is no means to recharge it renders the idea intrinsically unacceptable. Furthermore, a safety risk is produced as a result of the fact that the user may attempt to connect a battery charger to the device. If this connection is not secured by a fuse or breaker, it may result in short circuit circumstances, which almost invariably lead to damage

to property or even worse. In light of these considerations, it was decided that, if it was feasible to do so, the devices would be powered either directly by 120V AC or by the AC to DC converter, which is powered by 120V AC from the wall directly.

On the other hand, there are certain hardware components that cannot be separated from batteries due to their practicality. One of the cases is the mobile device that is used to execute the application; however, this is not a significant cause for concern because mobile charging is standardized and an extremely safe practice in every respect. On the PCB for the Moisture Sensor and the Main MCU are the batteries that are the main cause for worry. This is because these batteries are more difficult to access, and in order to make the design as efficient as possible for reasons related to sustainability, the devices are designed to have the lowest possible power consumption in order to guarantee a long system life. B cell "coin" batteries, which will be used for the PCBs of the moisture sensor, adhere to IEC 61960 REV, which is a standard that describes the battery life that can be anticipated from such batteries under specific operating circumstances. Both the power consumption and the charge of the battery will be monitored throughout the testing phase of the design. This will make it possible to test the battery to guarantee that it satisfies the requirements of the standard.

4.2.2 Optimizing Battery Longevity

The batteries that are going to be used in this project will not be exposed to temperatures that are significantly higher than normal. However, the coin batteries that are going to be linked to the PCB that is functioning as a moisture sensor will be exposed to water since it will be stuck in the soil, which will then be sprayed with water. Nevertheless, this specific battery type was selected because of this particular reason. When it comes to wet situations, coin batteries with a model name beginning with "CR" utilize lithium chemistry to build their voltage. This makes them significantly more suitable than alkaline-based batteries for usage in these settings. By using coin batteries that are based on lithium, they will be able to keep a sophisticated appearance with a limited amount of surface area that is exposed to water, while yet providing sufficient power to operate the moisture sensors.

4.2.3 Reliability and Maintenance Constraints

4.2.3.1 The process of corrosion

During the course of our investigation into moisture sensors, we came across the issue that a significant number of customers have expressed their dissatisfaction with the corrosive properties of various types of sensors, including direct contact electrode sensors. It would appear that the majority of the sensors that are constructed in this manner are only utilized for a single instance or for a little length of time. When it comes to the moisture sensor that we are going to use for our plants, we strive to prevent corrosion to the greatest extent feasible. This is because of the reasons stated above.

Electrolytic and galvanic corrosion are the two forms of corrosion that occur most frequently. For the purpose of this project, it is essential to have a solid understanding of both of these forms of corrosion because they are extremely similar to one another. When two different metals come into touch with one other and an electrical current is delivered between them, a phenomenon known as galvanic corrosion takes place. This is something that may occur on a printed circuit board (PCB) between the metal of the component and the metal from the trace that comes into touch with each other. After moisture has come into touch with this region on the printed circuit board (PCB), the electrical current will cause the metal that is more resistant and weaker to corrode more quickly. The result is that the voltage measurements between the components are inaccurate, and the components themselves deteriorate as a result.

Electrolysis and the chemical composition of the soil are two of the most prevalent causes of corrosion. The phenomenon known as electrolysis occurs when two distinct kinds of metal come into contact with water together. It is possible for electrolytes to attach to each of the two different metals, and it is also possible for a current to flow between the two metals because of the different metals. Consequently, this makes it possible for oxidation to take place within the metal, which will ultimately result in the metal gradually corroding away. Considering how acidic the water is, soil chemistry is another significant component of corrosion that must be considered. On the other hand, if the water in the soil is more acidic, then it has a greater number of H^+ proton ions. The result of this will be an increase in the number of electrons that are interested in pairing with the solitary hydrogen ions. Corrosion will take place at a quicker rate

in proportion to the number of electrons that are escaping from the sensor and entering the soil.

4.2.3.1.1 Erosion caused by electrolysis

The process of electrolytic corrosion takes place when an electrolyte, which is a conducting liquid, comes into contact with an anode and a cathode. Slivers of metal are able to pass through the electrolyte and come into touch with the other metal as a result of this. In the event that this is not addressed in the appropriate manner, the metal will begin to deteriorate over an extended period of time.

When an electrical current is present in a printed circuit board (PCB), a metal oxide will begin to develop between two traces if there is water present between the traces. This will occur if there is water present between the holes. This can result in a short circuit occurring in the printed circuit board (PCB), and if the metal oxide layer accumulates, this short circuit may become permanent over time. Any short circuit that happens in the circuit has the potential to result in undesired outcomes as well as complete failure of the circuit. We are going to make every effort to reduce the occurrence of this phenomena as much as we can because it is not ideal for any circuit.

4.2.3.1.2 Corrosion caused by galvanic current

The phenomenon known as galvanic corrosion takes place when two metals that are significantly different from one another come into contact with one another while an electrical signal is being transmitted through them in the presence of an electrolyte, which is often water. In the course of this process, one of the metals, known as the cathode, is more powerful than the other, known as the anode. Due to the fact that the weaker metal has a higher resistance, there is a greater amount of current that is transported through that metal. This effect will cause the anode to corrode more quickly, but the cathode will not be affected in any way by the corrosive phenomenon.

In the event that water comes into contact with the trace and the soldering connection on a printed circuit board (PCB), galvanic corrosion may take place. A conductive route will be created between the two metals as a result of this, and the anode will be the one to benefit from the electrical current. As a result, the

anode on the printed circuit board (PCB) will degrade at a considerably quicker rate than the cathode. This occurs due to the fact that solder frequently uses tin, but the trace on the printed circuit board (PCB) is constructed of copper. As a result of the different nature of these two metals, galvanic corrosion may take place. Over time, these connections on the printed circuit board (PCB) between the component and the trace will deteriorate to the point that a signal that is either too weak or not conveyed at all will be sent, which will ultimately result in the failure of the component.

The single-point resistive moisture sensors are the sites where this particular sort of corrosion is most frequently discovered. This is due to the fact that these sensors have been manufactured at a low cost and make use of metals of a lesser quality. There have been several reports of corrosion occurring with these sensors, and the degradation ultimately results in the failure of the sensor.

Table: Comparison of Electrochemical and Galvanic Deterioration

	Electrochemical Deterioration	Galvanic Deterioration
Causes	Electric current flowing through metallic material within an electrolytic solution	Physical connection of dissimilar metals immersed in an electrolytic medium
Conditions	Presence of wandering or leakage currents	Conductive solution creating electrical potential between dissimilar metals
Contributing Elements	Electrolytic conductivity, current intensity, and metallic composition	Metal compatibility and electrolyte conductivity
Outcomes	Rapid degradation of metallic structure	Progressive deterioration of the less noble metal
Mitigation	Minimize leakage currents, apply protective barriers,	Install cathodic protection, apply insulating coatings, use

	widen spacing of conductive paths	compatible metals
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4.2.3.1.3 Preventing Corrosion

In the process of attempting to fix corrosion, there are a wide variety of different sorts of remedies. Capacitive sensors, as opposed to resistive sensors, should be used as the first recommendation. Because the sensor does not require direct contact with the electrodes in the sensor and the water in the soil, capacitor sensors are sometimes referred to as corrosion resistant sensors. This is due to the fact that the sensor does not require an electrical connection. Through the utilization of a PCB soil moisture design, we are able to select the portion of the PCB that we wish to insert into the soil in order to determine the effect of the change in capacitance. We can determine the amount of water that is present in the soil by observing how fast or slowly the capacitor charges back up to its full capacity.

In spite of the fact that a printed circuit board (PCB) is mostly composed of copper, it is possible to apply a coating, such as gold or a gold-nickel alloy, over the traces in order to avoid corrosion. However, this may be an expensive endeavor. Another method for preventing corrosion on the printed circuit board (PCB) is to use solder masks, epoxy, or aerosol spray. Adding a case around the exposed components is yet another method that we may use to circumvent any corrosion that may occur on the printed circuit board (PCB) sensor. The electrical components would be protected from any stray water that could get onto them thanks to this. If you make sure that all of the components are dry, there will be no standing water on any of the metal components, which would prevent them from corroding.

We can also keep our components dry by making a three-dimensional model of the case for the printed circuit board sensor and then printing it out with a three-dimensional printer. It would be possible for us to prevent water from getting directly onto the components of the sensor if we constructed a casing around the components. Increasing the lifetime of the printed circuit board (PCB) would be of tremendous assistance to us.

4.2.3.2 The presence of salt

It is possible for the salinity of the soil to be one of the most significant elements that might influence the readings of a volumetric sensor. When discussing our project, the term "salinity" refers to the amount of salt that is present in the soil we are working with. A research project that was carried out by the National Library of Medicine investigated the ways in which salinity influences the output values of several sensors. According to the findings of their investigation, the majority of the moisture sensors that they examined incorrectly calculated the real moisture level in the plant when there was an excessive amount of salt present in the soil.

Because of the connection that exists between the salt of the soil and the electrical conductivity of the soil, this phenomenon takes place. According to the research that was presented earlier by the National Library of Medicine, the conductivity of the soil experiences a rise in proportion to the salinity of the soil. Electrons will be able to flow in a manner that is different from what is anticipated as a result of the rise in salinity. In the majority of cases, this effect is concerned with sensors that make use of capacitance-based readings. Under typical circumstances, the dielectric constant of the soil serves as the foundation for the observations that these capacitance moisture sensors take.

When it comes to moisture sensors that are based on capacitors, the capacitor is being discharged and is now waiting to be charged up again. Due to the fact that the dielectric material that the voltage is going through is now a more conductive medium, the amount of time that the capacitor is waiting to be charged again is now altered as a result of an increase in salinity. Due to the fact that the capacitor is now charging at a higher rate, this is causing the measurements to be inaccurate. It is possible to circumvent this problem by calibrating the sensor at a high salinity; but, in order to do so, you would need to maintain a high soil salinity level, which can be detrimental to the presence of many plant species.

Therefore, it is essential for us to take into consideration the salt level of the soil in order to guarantee that the measurements we obtain are accurate. In the event that we are having difficulty obtaining precise measurements for our project, this is one of the ways in which we may investigate and find solutions. So that we may do this, we can alter the soil that the plant is now growing in.

4.2.4 Constraints due to the Environment

The environmental limits are one facet of this project that can be simple to ignore if attention is not paid to them. It could appear that the environmental aspect of a project that involves growing plants indoors is the least of the concerns, but this is not necessarily the case under all circumstances. For instance, invading plant species have historically been responsible for billions of dollars' worth of damage. The United States Forest Service estimated that the yearly cost of controlling invasive species in the United States was five hundred million dollars as early as the year 2000, and this cost has continued to rise each and every year since then. When this is taken into consideration, the design is meant to allow the user to cultivate and develop only plants that are natural to the region in which they live, or non-native species that do not represent a threat to the populations of native plants. Nevertheless, despite the fact that the user is in charge of this danger, it is still an essential limitation to take into consideration when developing a technology that has the potential to make this improper behavior more convenient. When it comes to the species that they decide to cultivate in this automated indoor garden, it is strongly recommended that all users adhere to the local wildlife and forestry rules.

4.2.5 Limitations on the Security

One more significant limitation to take into account is the issue of security and vulnerability, particularly in relation to the wireless communication that takes place between the various devices involved in this project. More specifically, the communication that takes place between the phone and the main ESP32, as well as the communication that takes place between the ESP32s that are located on the moisture boards and the main ESP32. For every application in which data is exchanged and can be snooped upon, it is the responsibility of the design party to make the vulnerabilities known to the user in a clear and concise manner and to make an effort to address them to the greatest extent that is reasonably practicable. The information that is being exchanged for this project is completely harmless in every sense of the word. It is either the values from the moisture sensor or the values from the light sensor that are being sent between the main MCU and the app. Certain values are then returned to the user so that they may view them. No particular solutions have been implemented as a result of the fact

that there is no obvious breach of data in this situation that might result in significant harm to property or loss of information. Naturally, the Wi-Fi connection will adhere to the IEEE 802.11 standard, which incorporates built-in safety procedures. One example of this is Wi-Fi protected access 3, which encrypts the data that is transmitted over the network. On the other hand, despite the fact that the data being communicated is not very harmful, it is still essential to provide security in order to protect against any potential flaws that may exist inside the system. The prospect of unauthorized access to the wireless network is the key cause for concern. This access might provide hostile actors the ability to interrupt communication between the devices or intercept important data. The use of encryption methods such as WPA3 (Wi-Fi Protected Access 3) on all wireless connections is one method that may be utilized to overcome this challenge. With the implementation of WPA3, every data that is sent over a Wi-Fi network is encrypted, making it far more difficult for malicious actors to decrypt or take control of the transmission. Additionally, the utilization of Secure Sockets Layer (SSL) or Transport Layer Security (TLS) for communication between the mobile application and the ESP32 can further safeguard the data that is being transferred. This is accomplished by providing end-to-end encryption, which guarantees that the information is encrypted before it leaves the phone and continues to be secure until it reaches the ESP32.

Device authentication provides an additional degree of safety by guaranteeing that only approved devices are able to connect with the ESP32. In this particular scenario, the implementation of a device pairing procedure, in which the mobile application and the ESP32 participate in the exchange of authentication tokens or keys prior to the beginning of any data transmission, would offer an extra layer of protection. Additionally, the ESP32 itself ought to be designed to reject any attempts at illegal access, and it ought to include security mechanisms such as firewall rules in order to prevent exposure to ports that are not required. Last but not least, it is recommended that the ESP32 and the mobile app receive frequent software upgrades in order to rASepair any vulnerabilities that may have been detected. The project is able to limit the danger of security breaches by complying to certain security standards and best practices, such as employing WPA3, SSL/TLS, and device authentication. This is the case even if the data that is being transferred is not very sensitive. Through the implementation of this strategy, the system will continue to be dependable and secure for its users.

5.0 Comparison of ChatGPT with Other AI

5.1 Navigating the Landscape of AI-Assisted Research

The integration of generative Artificial Intelligence (AI) is a transformative element for a project like the GreenSync Smart Garden System. These tools can serve as powerful assistants, moving beyond the function of a simple search engine to become integral to design, problem solving, and documentation processes. A primary benefit is the significant acceleration of the conceptualization and documentation phases, allowing a team to draft architectural frameworks and explore a wide array of technological solutions in a fraction of the time traditionally required.

However, this research consistently underscores the limitations of AI in the context of complex, hardware dependent engineering. While AI excels at generating foundational code and high level strategies, its recommendations often lack the practical nuance required for real world embedded systems. Issues like the need for interrupt driven processes, power optimization for specific components, and understanding implicit project constraints are frequently overlooked by the AI. This highlights a critical learning outcome: AI is a powerful assistant that can augment human ingenuity, but it cannot replace the critical evaluation, hands on validation, and deep contextual understanding that defines human engineering judgment. The role of the engineer is to scrutinize, refine, and synthesize AI generated information to fit the precise needs of a project.

5.2 Case Studies in AI-Driven Component Analysis

AI generative assistance can be leveraged to research specific technical challenges and guide component comparisons. The following examples summarize the AI interactions, with the full text of the prompts and responses located in the appendix.

5.2.1 Example 1: Water Pump Selection

To compare different 12V DC water pump technologies, a detailed prompt was formulated requesting a comparison of peristaltic, diaphragm, and centrifugal pumps based on specific performance criteria (see Appendix, [AI 1]). The resulting AI generated response provided a highly detailed comparative analysis. It identified the diaphragm pump as a strong candidate, noting its robust flow rate of approximately 1.8 L/min and its crucial self priming capability, which simplifies system design. However, it also cautioned about potential drawbacks like pulsatile flow and noticeable mechanical noise (in the 50 to 60 dB range). The AI contrasted this with peristaltic pumps, which offer superior precision for dosing but have lower flow rates, and with centrifugal pumps, which are quieter but are typically not self priming, a critical design constraint. The analysis also extended to the electronics, recommending a MOSFET for power control and specific protective circuitry like a flyback diode to suppress EMF spikes.

This type of response is highly valuable because it provides a direct, data driven comparison based on the project's hypothetical constraints. The detailed breakdown affirms the advantages of a diaphragm pump for this application. Furthermore, the AI's warnings about pulsatile flow and electromagnetic interference (EMF) are key considerations for such a design, highlighting the need to incorporate components like a pulsation accumulator and a flyback diode.

5.2.2 Example 2: Sensor Battery Life Optimization

To research strategies for long term battery life, a specific prompt was used, detailing the components, communication protocol, and a target lifespan of 180 days (see Appendix, [AI 2]). The AI's synthesized reply outlined a comprehensive, multifaceted strategy for aggressive power management. For the microcontroller, it recommended leveraging the ESP32's Deep Sleep mode, where current consumption could drop to as low as 10 to 20 microamperes. For the sensor hardware, it proposed a power gating strategy using a low side MOSFET to completely de-power the sensor between readings, as even low power sensors have a quiescent current draw. On the firmware side, it suggested extending battery life by using longer sampling intervals, such as every 15 to 30

minutes, and optimizing communication by using the low power ESP NOW protocol to send data only when significant changes occur. To demonstrate the viability of this approach, the response included a conceptual power budget calculation, which estimated a potential battery life well over the 180 day target.

This interaction would be highly effective for research. By providing precise constraints, a detailed strategy is generated that is directly actionable for theoretical analysis. The response provides specific hardware and firmware recommendations, and the sample power budget allows for immediate validation of the battery life goals, providing a clear roadmap for potential implementation.

5.3 Triangulating Solutions with Competing AI Models

To address more complex challenges, one can query multiple AI platforms with the same prompt. This approach reveals that each AI often provides a valid but incomplete piece of the solution, requiring human synthesis to create a robust theoretical design. For this research, a complex, multi criteria prompt was given to ChatGPT, DeepSeek, and Claude to propose a corrosion prevention strategy for a PCB soil moisture sensor (see Appendix, [AI 3]).

5.3.1 ChatGPT

ChatGPT's response focused on surface level protection methods, providing a solid foundation of standard industry practices. Its key recommendations included applying a thin acrylic conformal coating for general moisture protection, using a solder mask on non sensing areas, and utilizing Electroless Nickel Immersion Gold (ENIG) plating on the exposed sensor pads for its superior corrosion resistance and signal integrity.

5.3.2 DeepSeek

DeepSeek's advice represented a more rugged, physically robust solution. It recommended a complete epoxy potting of the board's main body using a specific marine grade compound for superior water resistance. Critically, it also introduced the concept of preventing galvanic corrosion between dissimilar

metals by recommending the use of 316 stainless steel for any external metal contacts.

5.3.3 Claude

Claude offered a unique and more holistic view, considering the entire lifecycle and material integrity of the sensor. It advised selecting a high TG (glass transition temperature) FR 4 board for its inherent resistance to moisture induced warping and degradation. It also focused on design elements like trace width and spacing to maintain sensor accuracy and uniquely suggested a potential long term maintenance protocol involving rinsing the sensor.

5.3.4 AI Comparison Synthesis and Conclusion

This multi AI comparison is profoundly valuable because no single platform provides the complete, optimal answer. A final, synthesized strategy would be a synergistic combination of these varied recommendations:

- **Foundational Resilience (from Claude):** The synthesized approach would prioritize a high TG FR 4 board material.
- **Bulk Encapsulation (from DeepSeek):** It would adopt the comprehensive epoxy potting strategy.
- **Precise Sensing Window and Plating (from ChatGPT):** This strategy would integrate the idea of a precisely defined sensing window with ENIG plating.
- **Galvanic Isolation (from DeepSeek):** It would also incorporate the use of 316 stainless steel for external metal contacts.

This research process demonstrates a powerful human AI collaboration. While the AIs provide intelligent components of a solution, the ultimate responsibility for critically evaluating and combining these components into a cohesive engineering design rests with the human engineer. A final design synthesized in this way would be superior to any single AI's suggestion.

5.4 Critical Assessment of AI Tools in an Academic Setting

When applying generative AI platforms to a complex engineering project like GreenSync, a clear pattern of benefits and drawbacks emerges, directly influencing the student learning experience.

Pros (Benefits)

- **Rapid Information Synthesis:** The most significant advantage is the AI's ability to instantly collate and compare vast amounts of technical data. For instance, when researching water pumps, the AI can synthesize datasheets, application notes, and forum discussions into a concise comparison of flow rates, power needs, and other features, a task that would manually take hours or days.
- **Multi Perspective Brainstorming:** Using different AI models (like ChatGPT, Claude, and DeepSeek) on the same problem acts as a virtual brainstorming session with multiple "experts." As seen in the PCB corrosion example, one AI might focus on coatings while another focuses on material science, providing a more well rounded set of potential solutions than a single source might offer.
- **Conceptual Scaffolding:** AI is excellent at creating a starting framework or "scaffold" for complex tasks, whether it's outlining a technical report, generating boilerplate code for a software module, or proposing an initial system architecture. This helps overcome the initial "blank page" problem and provides structure to the design process.

Cons and Limitations

- **Context Blindness:** AI models have no true understanding of the unstated, implicit context of a project. An AI might suggest a power saving strategy without knowing the specific battery chemistry being used or recommend a component without considering the physical space constraints of the enclosure. This requires the engineer to constantly provide highly detailed context.
- **Lack of Practical Nuance:** AI generated solutions are often theoretically correct but practically flawed. For an embedded system, an AI might generate code that works but is highly inefficient, uses blocking delays

that would be catastrophic in a real time system, or overlooks critical hardware optimizations like using DMA to free up the CPU.

- **Plausible Inaccuracies ("Hallucinations"):** AIs can generate information that is incorrect but sounds perfectly plausible. It might invent a function name, misstate a technical specification, or combine two unrelated concepts. This places the burden of rigorous verification and fact checking entirely on the engineer, as blindly trusting the output can lead to significant errors.

Impact on the Learning Experience in Senior Design

The use of these platforms creates a unique set of learning opportunities and potential pitfalls:

- **Benefit: Fosters Critical Synthesis Skills:** The most powerful learning experience came from the multi AI comparison for PCB corrosion. The platforms provided conflicting yet complementary advice. This forced a higher level of engineering thinking: not just finding an answer, but critically evaluating multiple partial answers and synthesizing them into a superior, cohesive solution. This directly mimics real world engineering where solutions are rarely monolithic.
- **Benefit: Teaches Precision in Problem Definition:** A major lesson was in prompt engineering. An initial vague prompt like "How to make my sensor last longer?" yields a uselessly generic response. Learning to formulate a precise engineering query, specifying the exact components, operating environment, and performance metrics, is a skill in itself. This process teaches students to define a problem with the technical precision required for a real engineering task.
- **Harm: Risk of Superficial Understanding:** A significant danger is accepting an AI's answer without understanding the underlying principles. For example, if a student accepts a block of code for controlling a motor without understanding why a flyback diode is necessary, they haven't learned circuit protection; they've only learned to copy and paste. This can create a false sense of competence and lead to shallow learning.

- **Benefit: Identifies and Fills Knowledge Gaps:** When an AI provides a high level but incomplete answer (e.g., "use a MOSFET to control the sensor power"), it acts as a signpost. It highlights a necessary component but doesn't explain the implementation details (e.g., choosing N channel vs. P channel, calculating the required gate resistor). This prompts the student to recognize a gap in their own knowledge and drives them to perform focused, deeper research on that specific topic, leading to more robust learning.

5.5 Concluding Analysis on Human-AI Collaboration

Ultimately, the integration of generative AI into a project like GreenSync is an invaluable and transformative aspect of the senior design experience. While these platforms serve as powerful accelerators for research and initial design, the most profound lesson is in recognizing their inherent limitations. This research consistently demonstrates that AI generated output, while often theoretically sound, requires rigorous human engineering validation to address its frequent lack of practical nuance and real world context. The process of synthesizing complementary, and at times conflicting, advice from multiple AI platforms underscores that the true value of these tools lies in their ability to broaden an engineer's perspective, not to provide a single, definitive answer. Therefore, this exploration concludes that generative AI is best wielded as an augmentative tool, one that enhances, rather than replaces, the indispensable critical thinking, hands on validation, and creative problem solving skills that define the engineering discipline.

Disclosure: The final text of this report, including all analyses and conclusions, were written by the authors but with the aid of AI platforms. ChatGPT, DeepSeek, and Claude were used to rephrase and correct grammar errors. As well as generating the responses to the prompts documented in appendix E which were solely used for research purposes.

Chapter 6: Hardware

6.1 MCU PCB Schematic

6.1.1 ESP32

The ESP32 microcontroller will operate using power supplied through a 3.3V voltage regulator. For USB communication functionality, the system will incorporate a HiLetgo CP2102 USB-to-TTL UART development board. This converter module will establish connections with the ESP32 through four essential pins: VCC for power, TX and RX for data transmission (utilizing pins 35 and 34 respectively on the ESP32), and GND for ground reference. The ESP32 will implement the I2C communication protocol, with pin 14 designated for the SCL (serial clock) line and pin 16 assigned to the SDA (serial data) line. During the PCB design phase, multiple test points will be strategically incorporated throughout the board to facilitate connection verification and troubleshooting.

6.1.2 Regulators

The custom PCB design features dual voltage regulation circuits consisting of both 3.3V and 5V boost converters. These regulators draw power from a PCIFR18650-1500 lithium iron phosphate (LiFePO_4) battery that delivers 3.2V nominal output with 1.5Ah capacity.

For the 3.3V power supply, the TPS613221ADBVT serves as the primary regulator—a synchronous boost converter with high efficiency that accepts input voltages between 0.9V and 5.5V, making it ideal for battery-operated systems with low voltage requirements. This component offers a peak switch current limitation of approximately 1.2A, providing sufficient margin for peak power demands, especially when the ESP32 performs RF transmission operations.

Following manufacturer guidelines, the inductor selection fell within the recommended 0.7 μH to 13 μH range, with 4.7 μH chosen as the optimal value to achieve proper balance between physical dimensions, stability requirements, and current capacity. Output filtering utilizes a 22 μF ceramic capacitor, selected from the acceptable 4.7 μF to 100 μF range, which maintains voltage stability during varying load demands. Near the battery connection point, an extra bypass capacitor helps mitigate voltage drops that may occur during initial power-up or rapid load transitions.

The TPS613222ADBVT handles 5V regulation, sharing pin compatibility and similar specifications with its 3.3V counterpart. While not utilized in the current hardware iteration, this 5V supply remains part of the circuit design to accommodate potential future additions requiring elevated operating voltages. Component selections for both regulators remain consistent, using matching inductors and capacitors to streamline procurement and board layout.

Manual power control capability exists through an integrated power switch within the regulator circuitry, facilitating controlled power states for testing procedures and field deployment. The 3.3V supply serves the ESP32 microcontroller along with various sensors and logic-level components. Implementation will follow established PCB design principles, including minimized trace lengths for switching signals, thermal via implementation for heat management, and strategic capacitor positioning to maintain regulator performance while reducing electromagnetic interference.

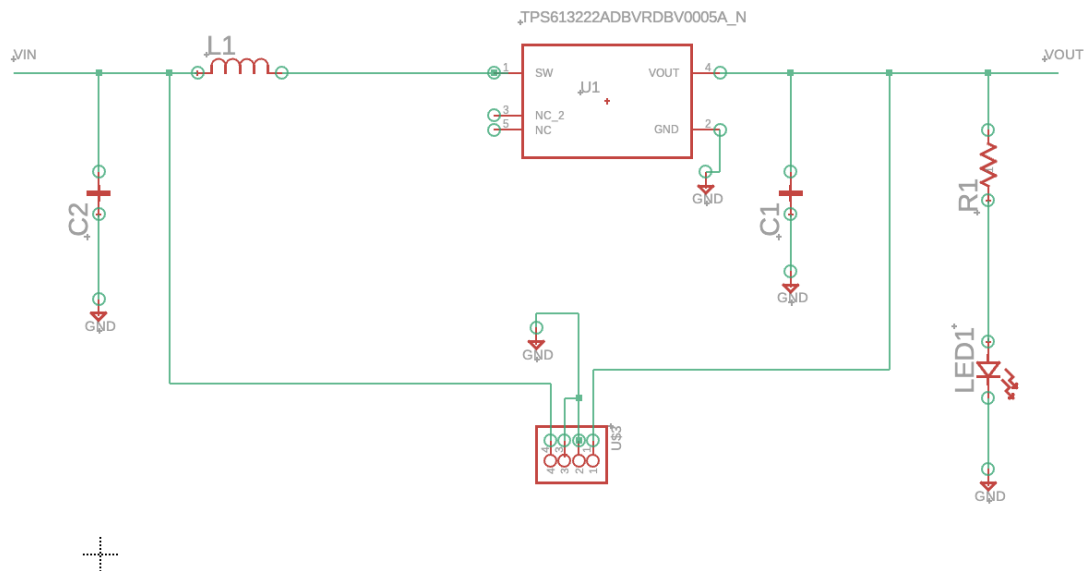


Figure: Regulator Schematic

6.1.3 Sensors

Environmental monitoring for an individual plant will be achieved through the integration of an AHT20 humidity and temperature sensor alongside a VEML7700 ambient light sensor. Both components utilize I²C communication

protocol for data transfer. Since these sensors possess distinct, factory-assigned I²C addresses, they can operate on a shared I²C bus without address conflicts, removing any requirement for multiplexing hardware.

Both sensors' SDA (data) and SCL (clock) connections will be wired in parallel configuration and connected to the ESP32's I²C interface pins—specifically GPIO13 for SDA and GPIO14 for SCL. Reliable I²C communication requires pull-up resistors of 1 k Ω value connecting each signal line to the 3.3V power rail, following specifications outlined in the respective sensor documentation.

This streamlined approach minimizes hardware requirements while optimizing both PCB real estate and power consumption, creating an efficient solution for cost-sensitive, battery-operated prototypes. The ESP32 will execute periodic sensor polling via the I²C bus to collect environmental data for immediate monitoring applications or automated control algorithms. Design implementation will incorporate established PCB best practices, including shortened I²C trace routing and placement of decoupling capacitors adjacent to each sensor's power input, ensuring communication integrity and operational stability.

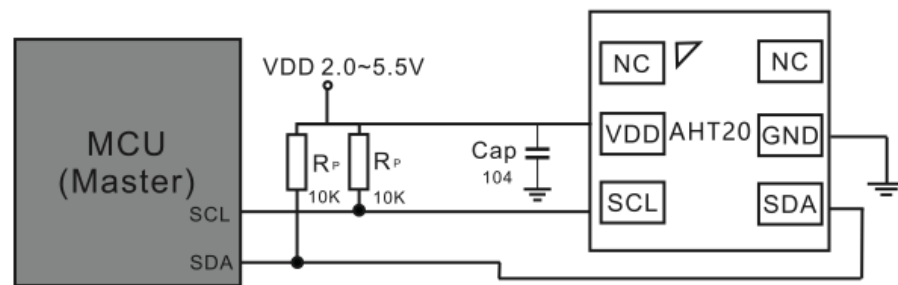


Figure: AHT20 sensor within typical application circuit

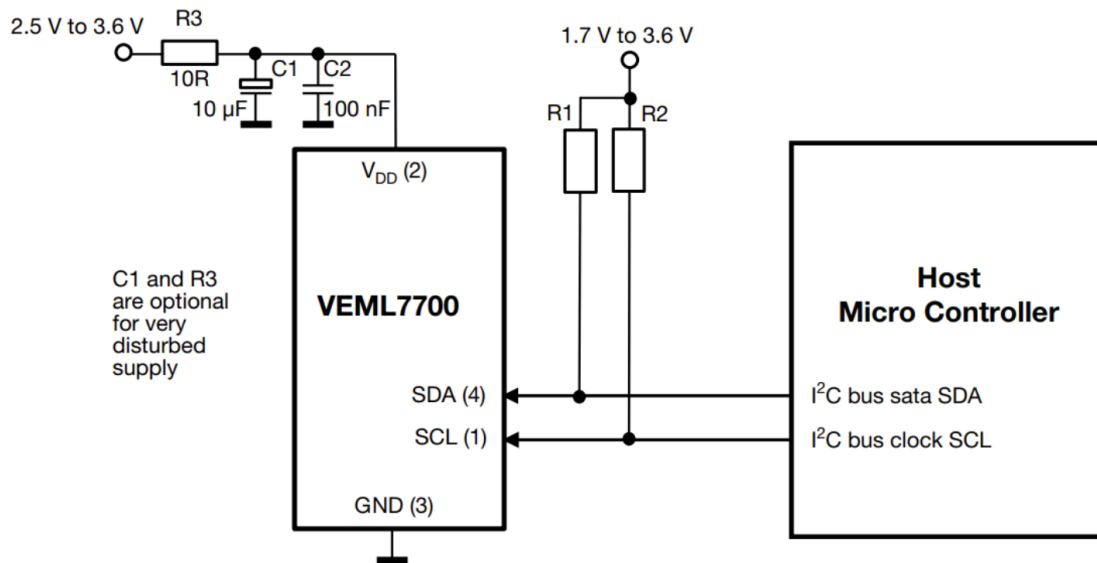


Figure: VEML770 sensor within typical application circuit

6.2 Water Pump Subsystem Block Diagram

The relationship between system components and their respective power connections is depicted in the included block diagram. A 12V AC-to-DC converter serves as the primary power source, simultaneously supplying both the diaphragm water pump and the 12V solenoid valve through a common power rail.

Water supply originates from a plastic reservoir located below the plant platform. The pump pressurizes the PVC distribution line to a maximum of 50 PSI, triggering an integrated pressure switch that automatically halts pump operation to preserve system pressure. The pressurized water remains static within the plumbing network due to the solenoid valve's normally closed state, which blocks any unintended water release.

Irrigation control relies on continuous soil moisture sensor feedback. Upon detecting moisture levels falling below predetermined parameters, the ESP32 microcontroller energizes a GPIO pin to trigger the solenoid valve opening. This action permits water passage through the valve into drip irrigation tubing that targets the plant's root system.

When sensor readings indicate soil moisture has reached the upper threshold, the microcontroller deactivates the GPIO signal, closing the solenoid valve and terminating water delivery. The pump maintains operation until its pressure switch registers 50 PSI system pressure and initiates automatic shutdown. This design maintains optimal system pressurization independent of irrigation cycle frequency.

Critical design factors include AC-to-DC power supply specifications, which must accommodate concurrent operation of the pump, solenoid valve, and LED growth lighting system. Power supply selection followed established engineering protocols by calculating peak current requirements for all components during maximum load conditions, then incorporating a 10% safety factor. The chosen converter satisfies these specifications while guaranteeing stable performance across all anticipated operating scenarios.

The water subsystem functions without requiring a custom PCB, as both the moisture sensor and microcontroller operate as discrete hardware units. Their individual hardware implementations, encompassing PCB designs and voltage regulation circuits, receive comprehensive coverage in later report sections. The implementation utilizes a 12V solenoid valve appropriate for direct electrical connection, enabling smooth integration with the control architecture.

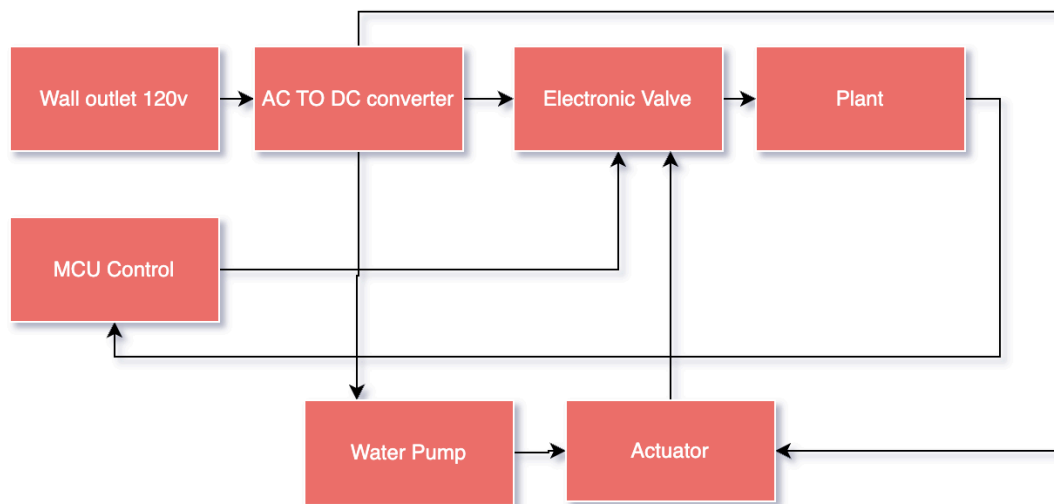


Figure: Waterpump subsystem Diagram

6.3 Moisture Sensor

The soil moisture sensing subsystem designed for individual plant monitoring incorporates multiple interconnected components. The configuration establishes connections between each element and the ESP32 microcontroller while defining interactions among the sensor, power infrastructure, control mechanisms, and user interface components.

Power delivery begins with a standard 120V AC wall outlet serving as the main energy input. Voltage conversion and regulation occur through an AC-to-DC converter that reduces and stabilizes the voltage to provide appropriate DC power levels for the ESP32, 12V water pump, and electronic solenoid valve. Converter specifications account for the cumulative current requirements of all components plus an additional 10% safety factor, guaranteeing reliable performance across varying load scenarios.

Moisture monitoring utilizes a single capacitive soil moisture sensor positioned within the plant's growing medium for continuous water content measurement. The sensor generates an analog voltage output proportional to soil moisture levels. The ESP32's integrated ADC (Analog-to-Digital Converter) transforms this analog signal into digital values suitable for software processing, enabling instantaneous decision-making based on moisture conditions.

Upon detecting moisture levels below established parameters, the ESP32 energizes a designated GPIO pin to open the solenoid valve, initiating water flow through drip irrigation tubing. Concurrently, the diaphragm pump extracts water from the storage tank and builds system pressure until reaching 50 PSI, at which point the pump's integrated pressure switch triggers automatic shutdown. When soil moisture reaches target levels, the ESP32 deactivates the GPIO signal, closing the solenoid valve and halting irrigation. The pump subsequently restores system pressure before shutting down automatically.

User interaction features include an LCD display presenting live information including moisture measurements, pump/valve operational status, and irrigation event logs. This visual feedback enables immediate system monitoring and plant condition assessment. The ESP32's wireless capabilities support communication

with mobile applications or web-based interfaces, facilitating remote sensor monitoring, threshold adjustments, and alert notifications, delivering intelligent plant care management from any location.

Additional design considerations include a 555 timer-based PWM (pulse-width modulation) generator circuit, which the current implementation does not utilize but remains noteworthy for its capability to provide duty-cycled power control for solenoid or pump operation. This circuit topology, commonly employed in smart irrigation applications, offers valuable insights into timing control methodologies and power modulation techniques that could enhance future system iterations.

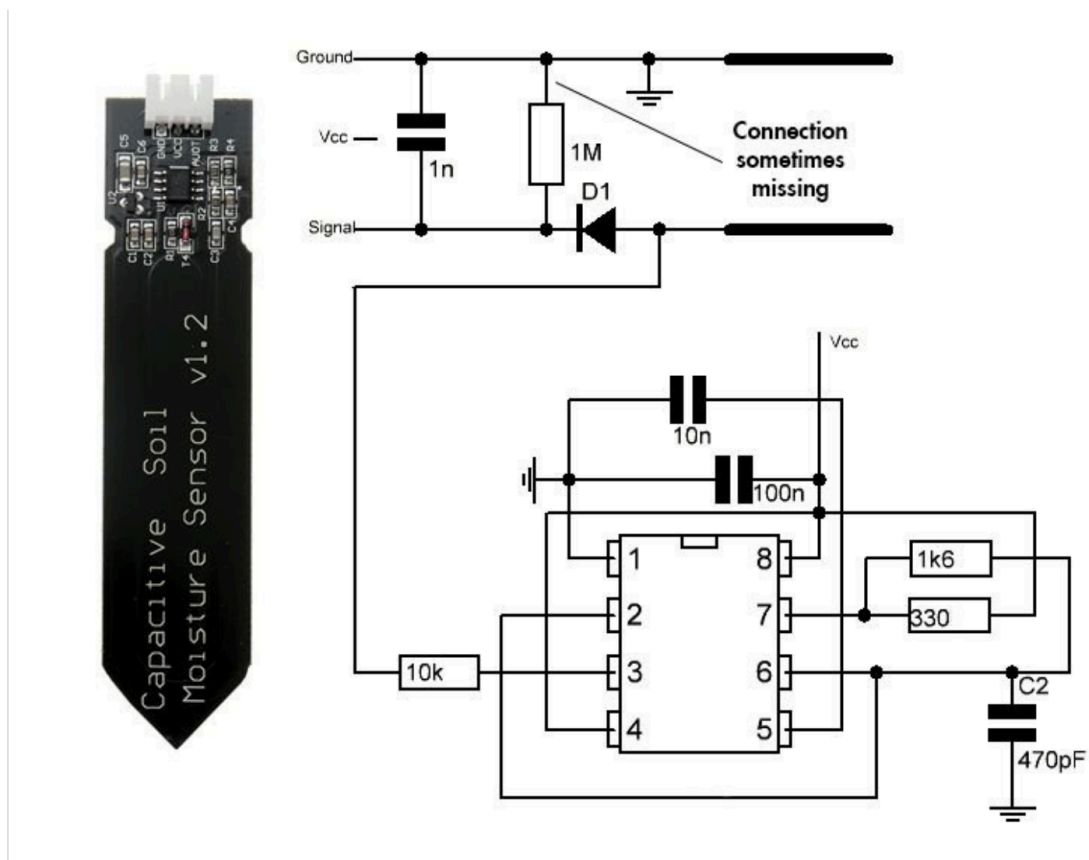


Figure: Typical Moisture sensor schematic

6.3.1.1 Voltage Regulation

The voltage regulation subsystem serves an essential function in delivering consistent and dependable power to delicate electronic components. This design produces a stable 3.0V DC output, critical for proper functionality of timing-based circuits like 555 timers and various low-voltage digital devices requiring steady power supplies.

IC1, a Low Dropout Regulator (LDO), forms the central element of this power subsystem. LDO technology excels in scenarios demanding precise voltage control with modest current requirements, maintaining regulated outputs even when input voltages barely exceed target levels. The LDO effectively reduces incoming voltage (commonly sourced from 5V supplies or batteries) to produce a smooth 3.0V output while minimizing thermal generation and voltage ripple—factors that could degrade overall system operation.

Multiple decoupling and bypass capacitors—designated as C1, C2, C6, and C8—enhance power supply stability throughout the circuit. These components eliminate high-frequency interference and suppress temporary voltage variations, creating a "cleaned" power signal. Such filtering proves essential for embedded applications where minor voltage irregularities can trigger unpredictable responses in timing-critical devices such as 555 timers or microcontroller analog sections.

Ground (GND) nodes throughout this circuit establish the common electrical reference for voltage readings and current return routing. Implementing a robust, low-impedance ground plane during PCB development reduces noise interference and strengthens the power distribution infrastructure's dependability.

This voltage regulation architecture guarantees all connected components access to clean, stable 3.0V power, fundamental for precise timing control and digital circuit operation. Absence of proper regulation would allow voltage fluctuations to introduce timing errors, erratic sensor outputs, or irregular system responses. The combination of LDO-based regulation and appropriate capacitive filtering delivers consistent performance across all essential components regardless of load variations.

6.3.1.2 555 Timer Pulse Generation

The pulse generation subsystem utilizes the TLC555CDR (IC2)—a low-power CMOS variant of the classic 555 timer. This versatile component serves as the system's timing core, generating consistent pulse trains or single-shot triggers based on its configuration. Within smart irrigation applications, the 555 timer controls timed operations including valve actuation periods, sensor polling frequencies, and periodic status notifications.

The TLC555CDR's timing behavior depends on its associated passive components forming an RC timing network. Resistors R3 (330 Ω) and R4 (1.6 k Ω), combined with capacitors C4 (100 nF), C5 (470 pF), and C7 (10 nF), establish the output pulse width and frequency parameters. Component selection ensures consistent timing signals appropriate for triggering control logic or synchronizing system events. The small-value C5 capacitor reduces timing jitter while enhancing short-duration pulse accuracy.

The 1N4148WS diode (D1) significantly influences the timing capacitor's discharge pathway, creating asymmetrical charge and discharge sequences. This configuration provides enhanced control over pulse width modulation (PWM) characteristics or non-standard duty cycles according to specific requirements. Diode integration improves pulse consistency and eliminates potential timing overlap or drift during continuous operation.

This pulse generation implementation delivers a reliable, economical timing solution for embedded systems, particularly beneficial in applications demanding deterministic operation with minimal resource consumption. Low power requirements, excellent stability, and adjustable output properties make this circuit ideal for automated irrigation, environmental monitoring, and control systems requiring accurate time-based activation.

The design functions as a modular subsystem readily customizable through component value modifications or integration with supplementary sensors, actuators, or communication interfaces. Operating independently as a pulse generator or incorporated within comprehensive embedded architectures, the TLC555CDR-based timing circuit establishes a dependable foundation for real-time control implementations while offering valuable educational insights into timing circuit design.

6.4 Lighting Subsystem Block Diagram

The block diagram below illustrates the lighting subsystem tailored for a single-plant environment, detailing component interconnections and their associated power supply paths. This subsystem plays a critical role in regulating plant growth conditions by dynamically adjusting light intensity and spectrum based on real-time sensor feedback and user-defined parameters.

As with the water delivery system, power is supplied through a 12V AC-to-DC converter, which provides regulated DC voltage to all lighting-related components, except for the ESP32 microcontroller, which is powered separately via its onboard 3.3V regulator. The central control component in this subsystem is the Shelly RGBW2, a Wi-Fi-enabled smart LED controller that allows precise dimming and color tuning of RGB LED light strips. The Shelly unit supports both 12V and 24V input, and in this application, it is operated at 12V for compatibility with the power supply used across the system.

The Shelly RGBW2 establishes a wireless connection with the ESP32, receiving control signals via the local Wi-Fi network. Based on commands issued from the mobile application interface, the ESP32 adjusts brightness and color output to meet the specific light requirements of the plant. This control includes smooth dimming, color blending, and on/off scheduling, offering full-spectrum lighting customization to simulate optimal growing conditions, including daylight cycles and intensity transitions.

To provide feedback for closed-loop control, a VEML7700 ambient light sensor is positioned near the plant to monitor light intensity in real time. This sensor communicates with the ESP32 over the I²C bus and returns lux measurements that the system uses to evaluate lighting effectiveness. The ESP32 analyzes these readings and adjusts the output of the Shelly-controlled light strips accordingly, ensuring the plant receives the appropriate amount of light based on its species-specific needs or programmed care profile.

As with other subsystems, careful consideration is given to the power budget of the AC-to-DC converter, which must simultaneously support the lighting system, solenoid valve, and water pump. The converter was selected to handle the combined peak current draw with an added 10% safety margin, ensuring stable and reliable performance under all operating conditions.

No custom PCB is required for the lighting subsystem itself. The light sensors are preassembled modules with onboard I²C breakout connectors and are directly wired to the MCU. The ESP32 PCB design—which handles system logic and

control—will be covered in a separate subsystem section. This modular design approach reduces complexity, facilitates easier integration and testing, and allows for future expansion with minimal redesign.

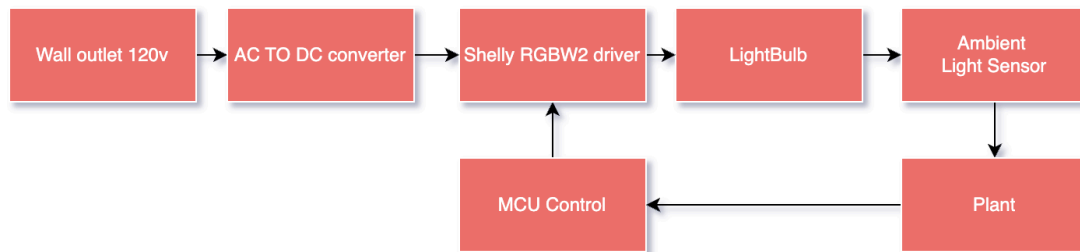


Figure: Lighting subsystem block diagram

6.5 Shelly RGBW2 Driver Schematics

The Shelly RGBW2 plays a central role in the lighting and control architecture of this system, serving as a Wi-Fi-enabled relay and LED driver. In this single-plant application, the Shelly's functionality is leveraged both for wirelessly controlling the RGB LED grow lights and as a smart on/off switch for the 12V DC solenoid valve used in the irrigation subsystem. Its compact footprint, direct integration with Wi-Fi networks, and compatibility with both 12V and 24V DC systems make it a practical and flexible choice for small-scale smart agriculture applications.

When configured in LED control mode, the Shelly RGBW2 can dim and color-mix standard RGBW LED strips, enabling fine-tuned light intensity and spectral composition based on plant-specific needs. This feature allows the ESP32 to remotely adjust lighting conditions using color blending and pulse-width modulation (PWM), achieving optimal photosynthetic response. For this application, it is operated in 12V mode to match the system-wide DC supply and ensure compatibility with other components such as the pump and valve.

Alternatively, when configured in generic switch mode, the Shelly RGBW2 can act as a wireless relay driver, providing on/off control over non-lighting devices—such as a 12V solenoid valve—through its output terminals. In this configuration, each output channel is effectively a remote-controlled low-side

switch that can be toggled via commands from the ESP32 microcontroller through a local network. For this single-plant system, only one valve is needed, and it is connected to a single channel of the Shelly output. The unused channels remain inactive or available for future expansion.

Shelly provides detailed wiring schematics for both LED lighting and generic load control configurations on its official documentation site. These can be followed with minimal adaptation: in the valve control setup, for example, the 12V DC solenoid valve is connected in place of the LED strip, with power routed through one of the RGBW channels. The ESP32 communicates with the Shelly via Wi-Fi, sending commands to toggle the output based on moisture sensor readings or user input from the mobile interface.

No custom PCB is required for integrating the Shelly RGBW2 into this system, as all connections are made via terminal blocks or screw terminals on the module itself. This allows for rapid prototyping and simplified installation without the need for additional circuit design. However, if desired, the system could be migrated in the future to a more compact and power-efficient alternative—such as an ESP32-based MOSFET switch or dedicated relay module—to reduce cost and eliminate dependency on third-party cloud services.

In summary, the Shelly RGBW2 provides a robust, network-ready solution for both lighting control and solenoid actuation in this smart gardening application. Its wireless capabilities, versatility, and ease of integration make it an ideal fit for the current project scope, with room for future scaling and customization.

White LED bulbs scheme

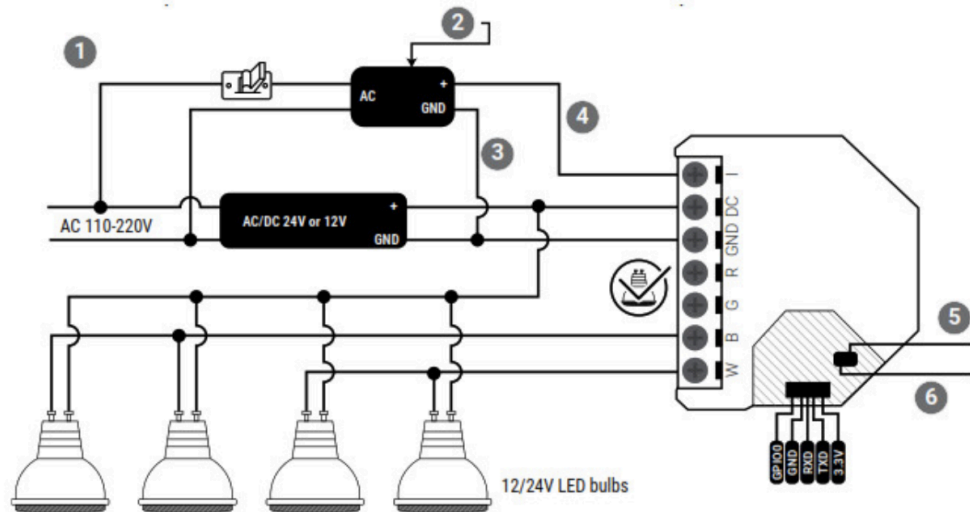


Figure: Shelly RGBW2 Driver Schematics

6.6 Camera:

To enhance plant monitoring and support long-term health tracking, the system incorporates an ESP32-compatible camera module to capture periodic images of the plant. For this application, the ESP32-CAM module is selected due to its compact design, low power requirements, and native integration with the existing ESP32 platform. This module combines an OV2640 camera sensor, microSD card slot for local image storage, and onboard Wi-Fi and UART connectivity—making it well-suited for standalone or networked image capture tasks within embedded IoT environments.

The OV2640 sensor provides a resolution of up to 1600×1200 (UXGA), more than sufficient for assessing plant growth, detecting discoloration, and documenting environmental changes over time. Configurable resolution and compression settings allow images to be optimized for bandwidth or memory constraints, depending on whether they are stored locally on an SD card or streamed over Wi-Fi to a cloud dashboard or mobile app.

The ESP32-CAM module operates at 3.3V, which aligns with the system's regulated voltage rail and avoids the need for level shifting. Power is supplied

through the same 3.3V LDO regulator used for the ESP32 mainboard and other sensors, ensuring stable operation. Like the ESP32 MCU, the camera module's current spikes during Wi-Fi transmission or image capture are brief but notable, so proper bypass capacitors should be placed near the module to handle transient demand and avoid brownouts.

In this system, the ESP32-CAM can either:

- Operate independently, triggered periodically via internal timers or external GPIO pulses from the main ESP32 controller, or
- Be integrated as a peripheral module that receives capture commands via UART or HTTP over Wi-Fi, allowing full coordination with the main irrigation and lighting systems.

Captured images can be:

- Stored on the microSD card onboard the ESP32-CAM for later review, or
- Uploaded to a cloud server or viewed in real-time through a web interface, leveraging the ESP32's built-in Wi-Fi capabilities.

For physical integration, the ESP32-CAM can be mounted in a 3D-printed camera bracket or enclosed in a weather-resistant housing for environments with high humidity or water exposure. The camera should be positioned to capture a top-down or angled view of the plant pot, ensuring visibility of leaves and stem structure for health assessments.

No additional PCB is required for the camera subsystem, as the ESP32-CAM is a self-contained module. Communication is wireless, and control logic can be incorporated via lightweight HTTP server code or GPIO signaling from the main ESP32 board. If desired, a MOSFET-based power switch can be added to cycle the camera module's power during off-hours, further conserving energy in battery-powered applications.

In summary, the ESP32-CAM module offers a cost-effective and seamless way to integrate visual monitoring into the smart plant system. It complements the existing ESP32 infrastructure, shares the same power supply, and provides

powerful capabilities for plant tracking, remote diagnostics, and automated photo documentation—all essential features in advanced smart gardening and environmental monitoring platforms.

Chapter 7: Software

7.1 Core System Software Design

For the GreenSync system, the firmware will be architecturally split into two key domains: one dedicated to the individual soil moisture sensor nodes and the other for the Central Control Unit, or CCU, that acts as the system's brain. This separation is an intentional and critical design choice that will enhance modularity, simplify debugging, and allow each distinct hardware component to be optimized for its specific task. This distributed approach means that the sensor software can be perfected for low power operation, while the CCU software can be focused on complex data processing and network management. The CCU will serve as the system's intelligent nexus, responsible for advanced data analysis, managing the network connection with the mobile application, and executing precise, calibrated control over the garden's lighting and irrigation environments.

For instance, each sensor node will be equipped with specialized firmware focused exclusively on efficient and accurate data acquisition. Its primary operational loop will involve reading the analog soil condition, performing an on chip analog to digital conversion, and then broadcasting this raw data packet over the wireless network. The CCU's more sophisticated firmware will receive these packets and will be responsible for all of the system's higher order logic. It will run a non blocking, real time control loop that continuously interprets the incoming sensor data, manages the Wi Fi connection to the user's mobile app, and makes calibrated decisions about when and for how long to activate the various environmental systems. The entire firmware design will emphasize responsive performance and robust power conservation strategies to ensure a seamless user experience and long operational life for battery powered components.

This state machine diagram illustrates the complete operational flow of an IoT sensor device. When the device first powers on through the Boot Sequence, it attempts to connect to a WiFi network in Network Client Module mode. If the connection fails due to a network timeout or wrong password, it switches to Access Point Module where it creates its own WiFi hotspot, allowing users to connect and provide correct network information. Once WiFi is successfully connected, the device proceeds to Hardware Init where it initializes and checks all sensors and components. If sensor readings are invalid (bad sensor values), it loops back to try initialization again; otherwise, when sensors are ready, it can either enter the Config Portal for user settings or proceed to the Monitor Loop. The Monitor Loop continuously checks sensors on a timer trigger schedule. When sensor changes are detected, the Data Handler processes this new information, leading to the Running State where the device is actively operating. If there's no activity, the device enters Power Savemode to conserve battery, from which it can be awakened by a wake signal to return to the Running State. Users can manually reset the device from the Access Point interface at any time. Eventually, all paths lead to System Halt when the device shuts down completely. This design ensures efficient power management while maintaining responsive sensor monitoring and network connectivity.

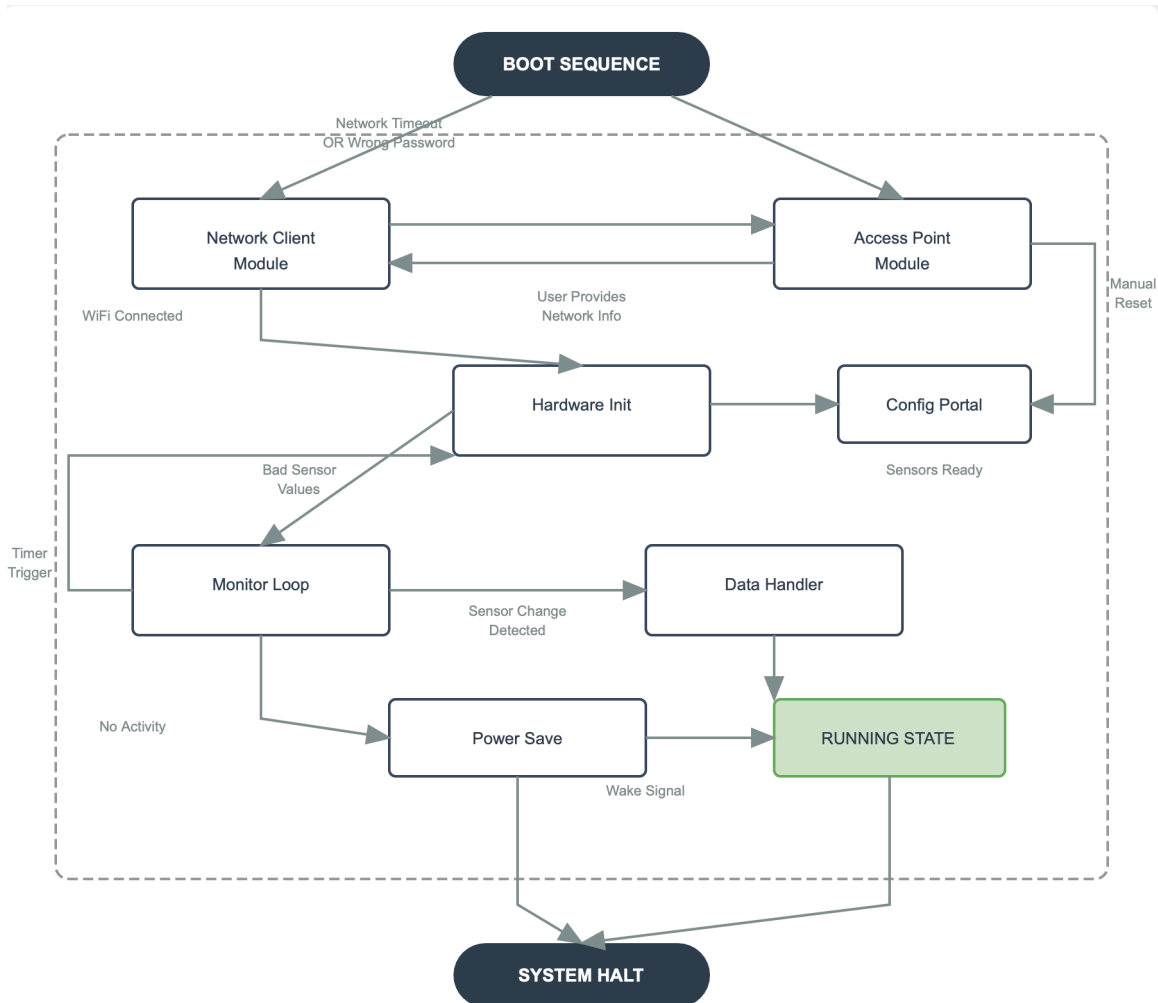


Figure: Software State block Diagram

7.1.1 Development Environment and Tools

For the crucial task of firmware development, the project will leverage the widely supported Arduino IDE, with embedded C++ serving as the core programming language. This strategic decision is rooted in pragmatism and efficiency. By choosing an environment that is already deeply familiar to the development team, the project bypasses the significant time investment required to learn a more complex, professional toolchain like PlatformIO or the native ESP IDF. This accelerated learning curve allows engineering resources to be focused directly

on developing the system's unique features rather than on mastering new tools. Furthermore, the immense global community behind Arduino provides an invaluable safety net, offering a vast repository of pre-vetted libraries, extensive documentation, and countless forum discussions that can dramatically speed up troubleshooting and development.

To facilitate collaborative development where multiple team members will work on different software modules in parallel, a centralized code repository will be established on GitHub. This version control system will be essential for tracking all changes, managing different feature branches, and providing the ability to roll back to previous stable versions in case of errors. This technical workflow, supported by active and disciplined communication on Discord, will be crucial for maintaining code integrity, preventing conflicting code merges, and ensuring all team members are working from a unified and up to date source.

7.1.2 Sensor Module Firmware

The GreenSync design will specify the deployment of multiple soil moisture sensor modules, all sharing a common hardware and software design for consistency and reliability across the entire garden environment.

GreenSync Sensor Module Operation



Figure: GreenSync Sensor Module Operational Cycle

The guiding philosophy for the sensor module's firmware is extreme power efficiency. To achieve a long operational life on battery power, the software's logic will be kept as minimalistic as possible. The firmware's sole responsibility will be to accurately measure the moisture level of the soil. All computationally intensive tasks, such as data analysis, comparison to user defined thresholds, or historical data logging, will be deliberately offloaded to the more powerful, mains powered CCU. As the flowchart in the figure illustrates, the sensor's task will be a simple and focused recurring loop: wake from deep sleep, collect a single data point, transmit it, and immediately return to deep sleep. This approach makes the sensor a highly optimized, low energy data collection endpoint.

7.1.3 Central Control Unit Logic

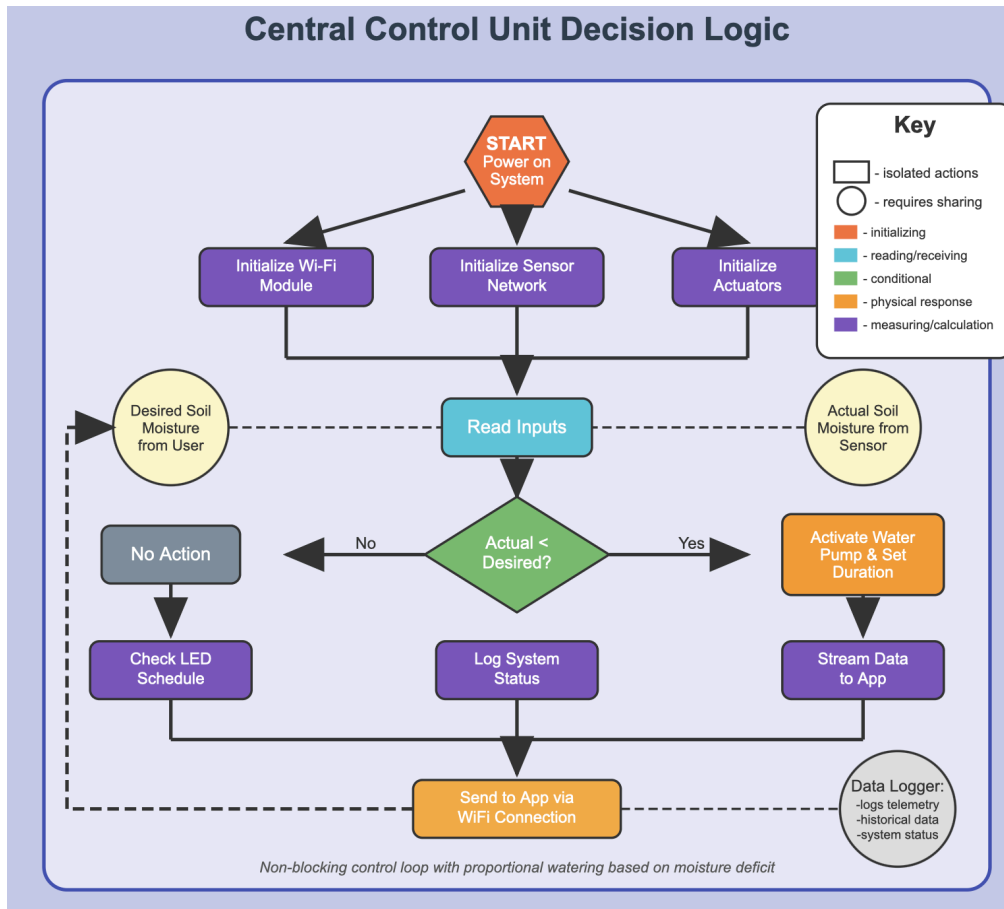


Figure: Central Control Unit Decision Logic Flowchart

The firmware for the main system's MCU will serve as the command center for the entire project, orchestrating every automated action the GreenSync system takes. This software, running on the main ESP32 processor, will be responsible for all intelligent operations. It will manage the two way communication link with the user's mobile application, receive and process data broadcasts from all active soil sensors, and directly command the system's physical actuators, including the water pump and the LED lighting arrays.

The CCU's networking logic will be built to handle simultaneous Wi Fi connections, maintaining a persistent link to the mobile app while continuously listening for incoming data packets from the broader sensor network. The mobile app will serve as the source for all user defined "setpoints" and configuration

data—such as target moisture levels and preferred lighting schedules—while the CCU will stream back real time telemetry. This will include current conditions, historical data charts, and overall system status, all for display on the user's device.

The core of the CCU's intelligence will lie in its advanced control algorithm. Rather than a simple on or off check, the firmware will calculate a "moisture deficit" by subtracting the current moisture value from the target value. The duration of the subsequent watering cycle will then be calculated to be directly proportional to this deficit. A small deficit might trigger a short, gentle watering, while a large deficit would result in a longer, more thorough cycle. This proportional control method is more sophisticated than a simple threshold trigger, as it will conserve water and actively prevent the system from overshooting the target moisture level, ensuring healthier soil conditions for the plants. The accuracy of this entire process will therefore be fundamental to the system's successful operation.

7.2 Mobile Application Framework

Flutter has been selected as the foundational framework for the user facing mobile application. This choice was based on Flutter's proven strengths in building performant, cross platform user interfaces from a single codebase, which is a significant advantage for development efficiency. Its ability to effectively manage real time data synchronization with external hardware like the ESP32 was also a key factor in its selection as the most suitable tool for this project. This approach allows for the creation of a consistent and high quality user experience on both iOS and Android devices without the need for separate development teams or efforts.

7.2.1 Application Development Stack

All application coding will be conducted within the VSCode IDE, enhanced with the official Flutter and Dart extensions for a seamless development and debugging experience. During the initial design and prototyping phase, Figma has been used as a critical planning tool to construct a complete, full scale interactive mockup of the application's UI and logic. This blueprint, which includes detailed user flow diagrams and screen layouts, will guide the

development team. The use of Figma's AI plugin, UXPilot, was also explored to rapidly prototype different UI concepts, ensuring a well considered and user friendly design from the project's inception.

To maintain a unified codebase and streamline project management, the application's source code will reside in the same GitHub Repository as the embedded firmware, organized in its own dedicated directory. This will provide a single source of truth for all software developed for the GreenSync project, simplifying the build and deployment process.

7.2.2 User Interface and Experience

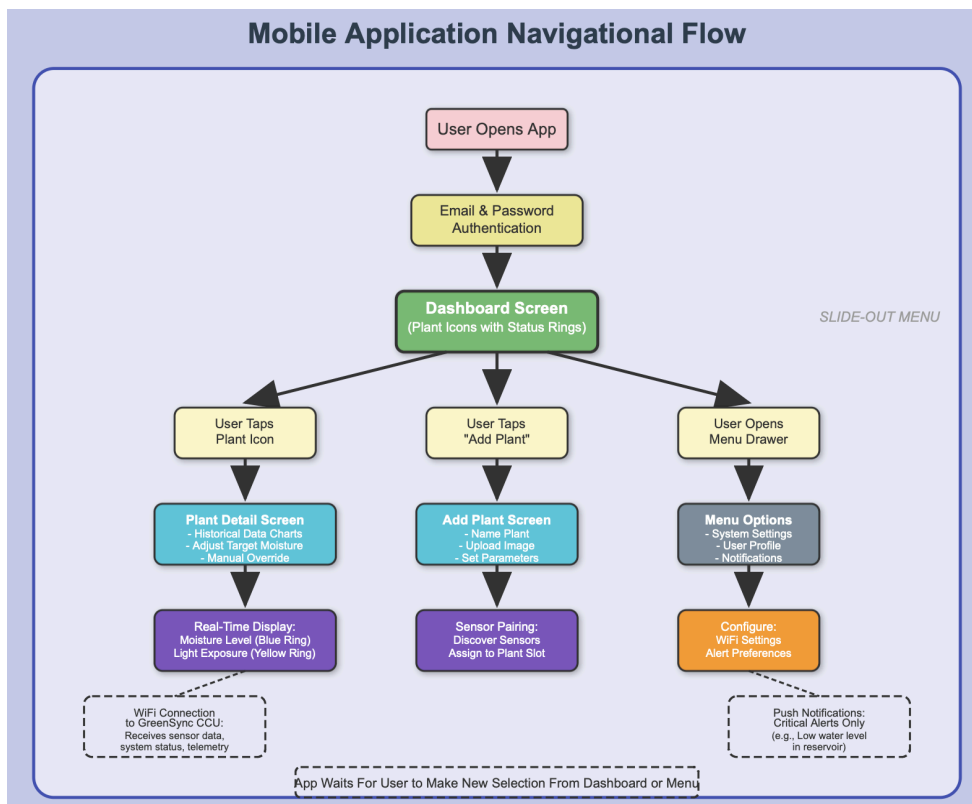


Figure: Mobile Application Navigational Flow

The GreenSync application is designed as an intuitive and visually informative dashboard for the user's indoor garden. Access will be secured through a standard email and password authentication system to protect each user's data and settings. The primary user interface is a central "Dashboard" screen, which

will display a dynamic icon for each plant registered to the system. These icons are designed to be informative at a glance, surrounded by status rings that will provide real time feedback on key metrics. For instance, a blue ring could represent the current soil moisture level, shrinking as the soil dries, while a yellow ring could indicate the cumulative light exposure for the day.

Tapping on a plant's icon will navigate the user to a detailed control screen for that specific plant. Here, they will be able to view historical data charts, precisely adjust target moisture levels, and manually override the automated lighting or watering schedules. Less frequently accessed sections, such as "System Settings" and "User Profile," are located in a slide out navigation drawer, a common mobile UI pattern that keeps the main interface clean and focused on the most important information. Push notifications will be reserved for critical alerts only, such as a low water level in the main reservoir, a design choice made to avoid overwhelming the user with non essential routine updates.

The "Add Plant" function within the app will allow users to register a new plant to an available slot in the GreenSync hardware. This straightforward process will involve naming the plant, uploading an optional image, and configuring its ideal environmental parameters. These user defined settings are the critical inputs that the CCU will use to inform its automated control logic.

7.2.3 User interface mobile application

The mobile application interface designs and system flowcharts presented in this section were developed using custom HTML and CSS prototyping techniques. Web based design methodologies were employed to create interactive mockups that accurately represent the intended user experience and system workflows. The mobile app screens were crafted using responsive CSS frameworks and modern design principles, allowing for realistic visualization of the GreenSync application's interface across multiple user scenarios including authentication, dashboard management, plant monitoring, and system settings. The accompanying flowcharts were designed using structured diagramming approaches with custom styling to clearly illustrate the operational cycles and decision logic of the sensor nodes and central control unit. This prototyping approach enabled rapid iteration and comprehensive visualization of both the

user facing interface design and the underlying system architecture, providing a complete visual representation of the GreenSync project's software components.

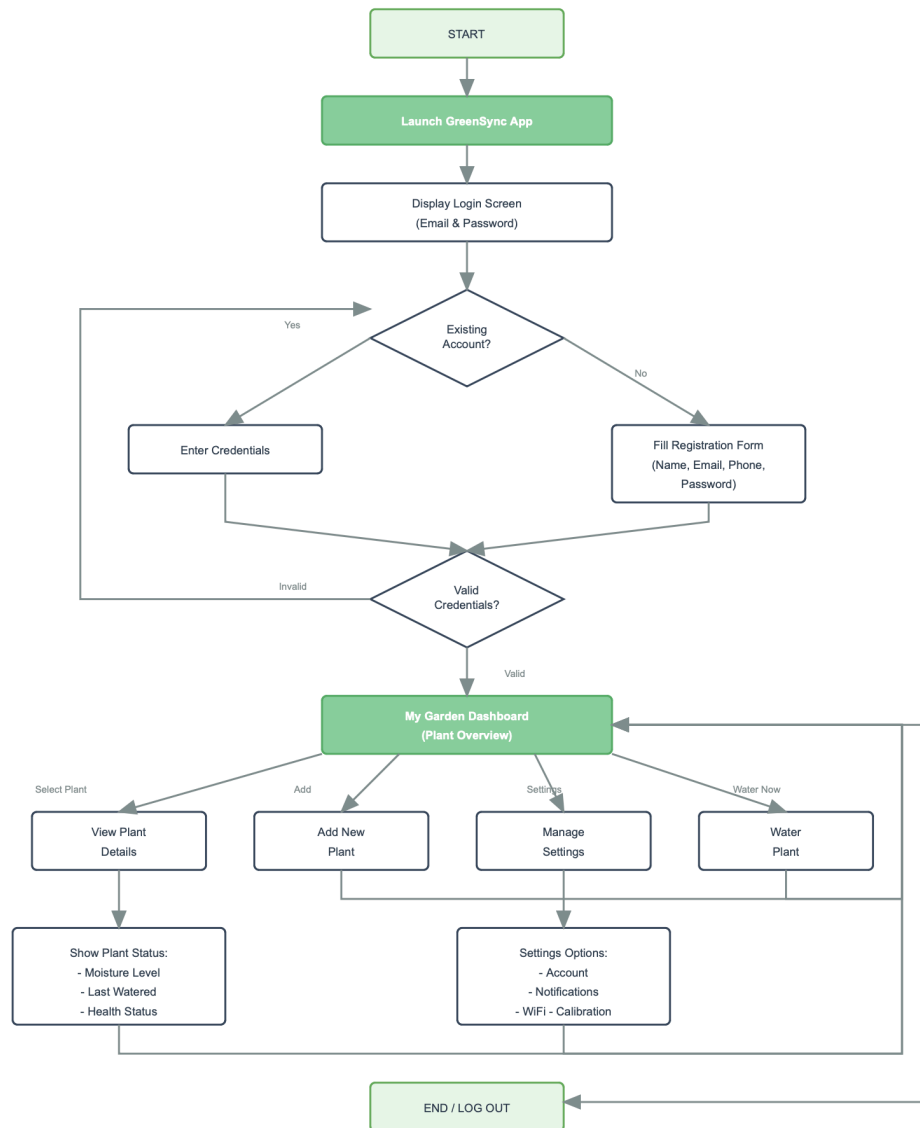


Figure: Mobile app Flowchart

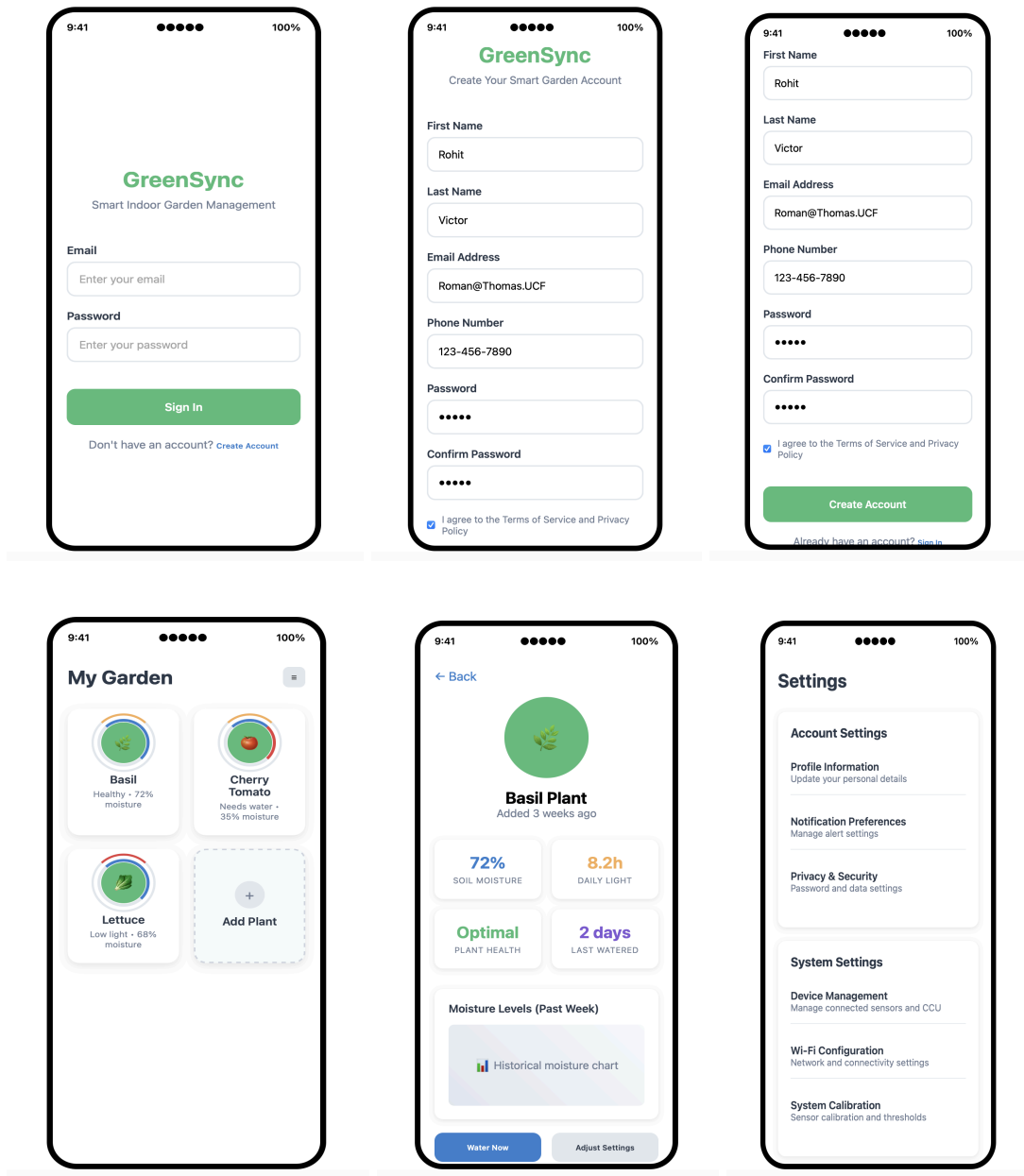


Figure: Users mobile interface

7.3 System Calibration and Constants

Adhering to modern software principles means avoiding hard coded values whenever possible, as they can make software brittle and difficult to maintain. However, for the GreenSync system, specific constants will need to be embedded in the firmware to serve as essential calibration benchmarks that allow the software to accurately interpret messy, real world data from the physical environment.

7.3.1 Soil Moisture Calibration Constants

In this system, hard coded constants will be necessary to translate the raw analog readings from the soil moisture sensors into a meaningful and standardized data format. Rather than a simple linear scale derived from two points, the system is designed to use a more sophisticated multi point calibration curve. Through empirical testing, raw sensor values will be recorded for several known soil states (for example, "fully dry," "damp," and "ideally saturated"). These data points, representing the unique response of the sensor hardware, will be stored in the firmware as an array. During operation, the ESP32 will use mathematical interpolation between these known calibration points to calculate a more accurate, non linear moisture percentage from any given raw reading. This method will provide a much more precise interpretation of soil conditions across the full moisture spectrum.

While formal testing has yet to be completed, it is hypothesized that the raw analog value for fully dry soil might be near 3100, while the value for ideally saturated soil could be in the 700 to 900 range. These values will be finalized during the hardware testing and calibration phase of the project.

7.3.2 Network Communication Constants

The system will leverage the built in Wi Fi capabilities of the ESP microcontrollers to create a private, low latency local communication network. Rather than relying on a traditional router based network that would add complexity and potential points of failure, the system will use a direct device to device communication method. This approach utilizes the Wi Fi hardware to send small, efficient data packets from the sensors directly to the Central Control Unit. This method is ideal for sending small packets of data with very low latency, which is perfect for real time sensor monitoring.

To establish a secure and manageable network, the system will use a dynamic pairing process rather than hard coding static MAC addresses. This process will be initiated by the user from the mobile application. When "Pairing Mode" is activated, the CCU will broadcast a special "discovery" message over its Wi Fi interface. New, un-paired sensors will be programmed to listen for this specific message. Upon receiving it, they will respond by transmitting their unique MAC address directly to the CCU. The CCU will then relay this information to the mobile app, which will display a list of newly discovered sensors. The user can then select a sensor and assign it to a plant, which securely adds its MAC address to a "whitelist" stored in the CCU's persistent memory. This method creates a robust and flexible system, allowing users to easily add or replace sensors without ever needing to modify and re-flash the firmware.

Chapter 8: System Fabrication

8.1 Layout of the PCB

We developed a dedicated power regulation module as a standalone unit, completely independent from other system components. This modular approach allows thorough validation and testing of the power supply circuitry in isolation, minimizing risk to other hardware during the development phase.

The power module features 32 mil trace widths, engineered to accommodate current demands reaching approximately 780mA under full load conditions. Due to the physical dimensions of both the circuit board and its mounted components, mechanical reinforcement will be required beneath the assembly. This support structure will protect against mechanical strain on connection points and maintain board integrity during operation.

Currently, the power regulation module remains in active development. The layout requires additional refinement before finalization, and all design decisions await approval from Dr. Weeks. The specifications and configuration may undergo revisions based on evolving project requirements and technical constraints that emerge during the review process.

8.1.1 Board for the 3.3V Regulator

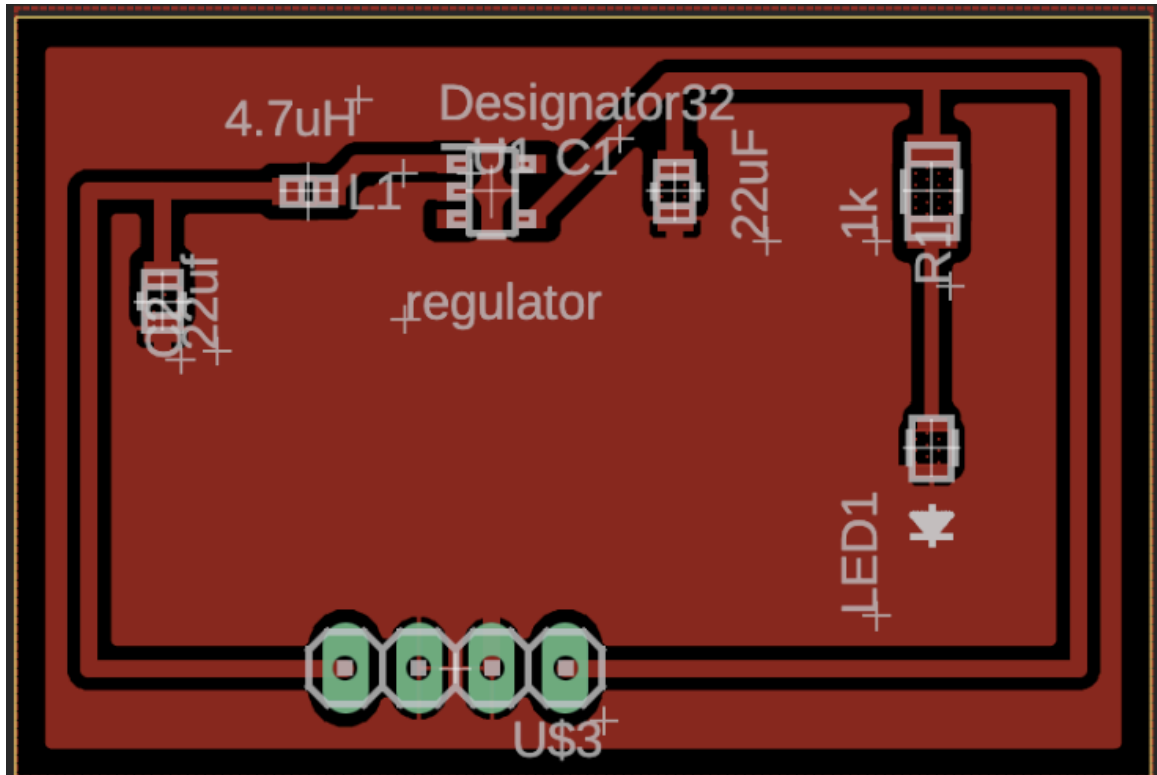


Figure: Regulators designed through Fusion360

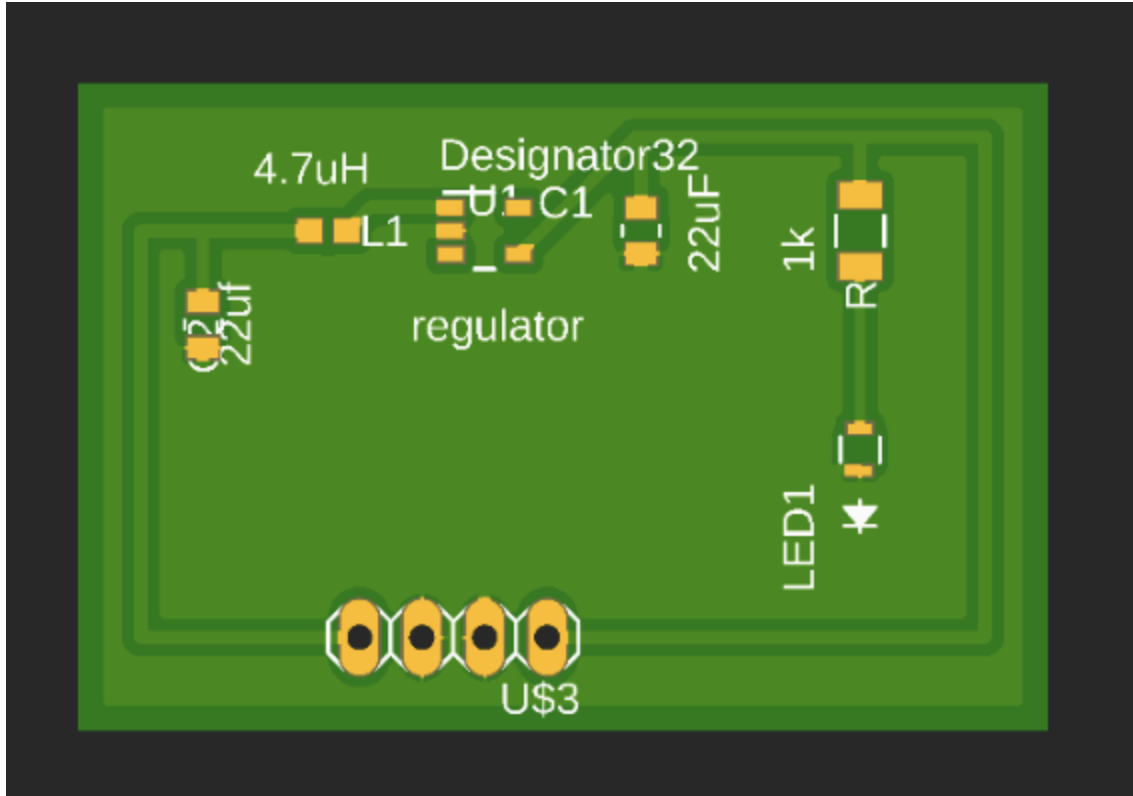


Figure: Regulators designed through Fusion360

8.1.2 The ESP32 Board

The microcontroller board housing the ESP32 represents a critical component of our system architecture, designed as a separate module to interface with the power regulation circuitry. This board will serve as the computational hub, managing wireless communications and system control functions once fully implemented.

The ESP32 module incorporates carefully calculated trace routing to support the microcontroller's various peripherals and communication interfaces. Board dimensions and component placement have been optimized to minimize electromagnetic interference while maintaining signal integrity across all connections. The layout considers thermal management requirements, particularly given the heat generation during wireless operation at peak power consumption.

This microcontroller board remains under active development, with significant design work still required before fabrication. The current schematic and layout await comprehensive review and approval from Dr. Weeks. Multiple aspects of the design may require modification based on testing results from the power module integration and any additional specifications that arise during the evaluation process. Final board characteristics will depend on performance requirements identified through ongoing analysis and consultation with the project advisor.

Chapter 9: System Testing and Evaluation

Chapter 10: Administrative Content

10.1 Component Comparison

Below we will list the items and components we will need during this project but are subject to change as we personally have never built something like this before. Below will be the main components and we will add a plus and minus buffer range in case we need to add or remove any of the components.

Table: Component list

CATEGORY	COMPONENT	PURPOSE	QTY	EST. COST (USD)
Control Unit	ESP32 Microcontroller	Main controller for sensors, logic, and communication	1	\$7.00
	Custom PCB	Integrates all hardware connections	1	\$10.00
	Power Supply (12V Adapter)	Provides power to the system	1	\$8.00
Water System	Capacitive Soil Moisture Sensor	Detects soil hydration level	1	\$2.50
	Mini Water Pump / Solenoid	Dispenses water when needed	1	\$6.00
	Tubing + Water Reservoir	Stores and channels water to plant	1	\$5.00
Light System	Ambient Light Sensor (BH1750)	Detects ambient light level	1	\$3.00
	LED Grow Light Module	Adds artificial light when insufficient natural light	1	\$8.00
	MOSFET / Relay Module	Switches grow light on/off based on logic	1	\$2.00
Camera System	OV2640 Camera Module	Captures daily time-lapse images	1	\$5.00
	MicroSD Card (16GB)	Stores images and possibly logs	1	\$6.00
	RTC Module (Optional)	Keeps time for image scheduling	1	\$2.50

User Interface	Mobile App (Custom)	Displays sensor and system data to user	1	Free (custom dev)
	Bluetooth/Wi-Fi (on ESP32)	Sends data from microcontroller to app	—	Included in ESP32
Miscellaneous	Jumper Wires, Connectors	General circuit prototyping and connections	—	\$5.00
	Enclosure	Housing for all hardware	1	\$7.00
	Status LEDs	Visual indicators for system feedback	2	\$1.00
Estimated Total Cost:				\$86.00

Note: These are a very rough estimate, and it is assumed that costs will end up being significantly more.

10.2 Project Milestones

The timeline below is an estimation of how things will go for our group. They are subjected to change in the case of certain due dates that are assigned during this semester and the fall semester for Senior Design 2. Below is a pseudo schedule that we hope to follow in order to progress smoothly through this project.

Table: Project Milestones table

Semester	Week(s)	Milestone
Summer	Weeks 1–2	Define project scope, goals, and deliverables; assign team roles
Summer	Weeks 3–4	Conduct research on plant needs, soil sensors, microcontrollers, and touchscreen options
Summer	Week 5	Compare component options and finalize bill of materials
Summer	Week 6	Order essential components and test soil sensor readouts using ESP32
Summer	Week 7	Create block diagrams and software architecture plans
Summer	Week 8	Write pseudocode for core features and interface design layout
Summer	Week 9	Draft early documentation and prepare progress presentation
Summer	Finals Week	Submit Summer Research Summary + Preliminary System Design
Fall	Weeks 1–2	Begin full system integration: sensors, pumps, UI, and ESP32–Pi communication
Fall	Week 3	Add real-time scheduling (RTC module or Pi time)
Fall	Week 4	Implement sensor-driven watering logic with live testing
Fall	Week 5	Build touchscreen interface with manual override features
Fall	Week 6	Add grow light control (optional stretch goal)
Fall	Week 7	Assemble full prototype in waterproof housing
Fall	Week 8	Run multi-day system validation tests
Fall	Week 9	Optimize logic, calibration, and UI feedback
Fall	Week 10	Prepare Final Report, Poster, and User Guide
Fall	Week 11	Polish final demo and presentation
Fall	Finals Week	Deliver Final Presentation + Submit Completed System

10.3 Workflow Distribution

Table: Work Distribution Table

Name	Primary Role	Secondary Roles
Roman Luknicki	Plant Care Delivery Subsystem	Growth Monitoring Subsystem, Custom PCB Design, Mobile App

Rohit Goeptar	Mobile Application Interface	Firmware Development System Integration & Testing
Victor M. Arteaga-Cuenca	Firmware Development	Mobile Application Interface, Environmental Sensing Subsystem
Thomas Parker 😞	Power Management Unit	Custom PCB Design

****subject to change***

Appendix A: reference

Appendix B: copyright permission

Appendix C: data sheet (if necessary)

Appendix D: software code (if necessary)

Appendix E: ChatGPT prompts and outcomes

[AI-1] Water Pump Comparison

- **Prompt:** "Evaluate compact 12V DC water pumps suitable for a smart plant watering system, specifically comparing a peristaltic pump (e.g., Kamoer KLP01), a small diaphragm pump (e.g., Shurflo 2088), and a brushless centrifugal pump (e.g., generic mini submersible). Focus on flow rate accuracy (ml/min), noise levels (dB), power consumption (Watts), self priming capability, and integration complexity with an ESP32 microcontroller for a target flow of 1.5 L/min."

- **Response:** "For your 1.5 L/min flow target in a compact 12V DC smart plant watering system, the Shurflo 2088 diaphragm pump presents a very strong candidate. It offers robust flow rates, typically achieving around 1.8 L/min at 12V... Crucially, it is a self priming pump, a significant advantage... However, diaphragm pumps inherently produce pulsatile flow... Peristaltic pumps... offer superior precision and consistency... but compact models often have lower maximum flow rates... Brushless centrifugal pumps are typically the quietest... A critical drawback is that they are generally not self priming... ESP32 integration for all three pump types typically involves a MOSFET switch... For diaphragm and centrifugal pumps, consider adding a flyback diode and an RC snubber circuit across the motor terminals to suppress EMF spikes..."

[AI-2] **Sensor Battery Life Optimization**

- **Prompt:** "For a capacitive soil moisture sensor PCB powered by a CR2032 coin cell battery and communicating with an ESP32 microcontroller via ESP NOW protocol, detail specific hardware and firmware strategies to achieve a minimum battery life of 180 days. Include recommended power down modes for both sensor and ESP32, optimal sampling intervals, and the impact of ESP NOW communication frequency on total power consumption. Provide a sample power calculation."
- **Response:** "To achieve a minimum battery life of 180 days with a CR2032 coin cell... the primary focus must be on aggressive power management.
 1. ESP32 Deep Sleep:... It should spend the vast majority of its time in Deep Sleep mode...
 2. Sensor Power Gating (Hardware Strategy): The capacitive soil moisture sensor must be completely de-powered (power gated) when not in use... Implement a low side MOSFET switch...
 3. Optimal Sampling Intervals (Firmware Strategy):... sampling every 15 to 30 minutes, or even hourly, would be ideal...
 4. ESP NOW Communication Efficiency:... Minimize the amount of data transmitted...
 Sample Power Calculation (Conceptual): ... Active current... 50mA (for ~500ms). Deep Sleep current = 20 μ A. Sample interval = 30 minutes... Estimated Battery Life = 220 mAh/0.816 mAh/day $\approx$ 269 days."

[AI-3] PCB Corrosion Prevention Strategy

- **Prompt:** "Propose a multi layer protection strategy for exposed copper sensor traces on a PCB that will be buried in typical potting soil, ensuring long term stability of capacitive measurements. Consider material compatibility, ease of manufacturing, potential impacts on sensor accuracy, and cost effectiveness. Specifically, what would ChatGPT, DeepSeek, and Claude each propose, and how might their distinct solutions be combined for an optimal, robust strategy?"
- **Response (Synthesized from ChatGPT, DeepSeek, and Claude):** The combined research from the three platforms led to a synthesized strategy that would be more robust than any single AI's suggestion. The final theoretical design would incorporate:
 - **(from Claude)** Using a high TG FR 4 board material as a resilient foundation to resist moisture and warping.
 - **(from DeepSeek)** Encapsulating the main body of the PCB in marine grade epoxy potting for a robust physical barrier against moisture.
 - **(from ChatGPT)** Creating a precise sensing window where the exposed traces are protected with ENIG (Electroless Nickel Immersion Gold) plating for superior, localized corrosion resistance.
 - **(from DeepSeek)** Using 316 stainless steel standoffs for any external metal contacts to prevent galvanic corrosion throughout the assembly.

Appendix F: etc.