GreenSync

-A Smart Home Plant Optimization System

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***Abstract* — GreenSync is a smart home optimization system that automates plant maintenance through integrated sensing control, and monitoring. The ESP32 microcontroller serves as the central unit, managing the capacitive soil moisture sensor, ambient light sensor (VEML7700), mini water pump, and LED grow light. A Raspberry Pi 4 complements the system by providing higher-quality image capture and live streaming through a USB camera. The custom five-board hardware design includes separate modules for sensors, pump relay, and regulated power distribution. Sensor data and system status are transmitted via MQTT to a mobile application, offering a reliable, low-cost, network-connected automation solution.**

***Index Terms* — Smart Home, Automation, ESP32, Raspberry Pi 4, Plant Optimization, MQTT, Mobile Application.**

I. INTRODUCTION

Indoor plant care offers environmental, psychological, and aesthetic benefits, yet maintaining optimal growth conditions remains a persistent challenge for many home gardeners. Inconsistent watering, inadequate lighting, and the absence of timely monitoring often lead to unhealthy or dying plants. GreenSync addresses these challenges by providing an automated, sensor-driven platform that optimizes watering and lighting through intelligent control and feedback.

The system centers on an ESP32 microcontroller that manages soil moisture and ambient light sensing while controlling a mini water pump and LED grow light to sustain ideal plant conditions. A Raspberry Pi 4 complements the system by handling high-quality image capture and live video streaming through a USB camera. GreenSync's companion mobile application expands functionality beyond monitoring by integrating computer vision for plant recognition, sensor data visualization, real-time live streaming, and an AI-assisted chatbot that helps users diagnose plant health issues.

Designed as a low-cost, scalable solution, GreenSync combines embedded system design, environmental sensing, and intelligent software into an integrated smart home platform. By merging automation with adaptive user interaction, the system demonstrates how technology can simplify plant maintenance while promoting sustainability and engagement.

II. SYSTEM DESIGN OVERVIEW

The GreenSync system automates the essential processes of plant maintenance through integrated sensing, control, and monitoring. The architecture is organized into five primary hardware modules: a main control board, power regulation board, soil moisture sensor, ambient light sensor, and pump relay board. The ESP32 microcontroller serves as the central processing unit, acquiring sensor data, managing thresholds, and operating the LED grow light and mini water pump accordingly.

A Raspberry Pi 4 supplements the design by managing the USB camera for high-quality imaging and livestreaming to the mobile application. Communication between hardware and software is achieved through MQTT, enabling real-time transmission of environmental data and actuation states. The mobile app provides users with an interface for live system feedback, plant recognition, and AI-based assistance for diagnosing plant health. Designed for efficiency and scalability, GreenSync combines embedded control, intelligent feedback, and wireless communication into a unified platform for smart home plant care.

III. SYSTEM HARDWARE COMPONENTS

At the core of the system is the **ESP32 microcontroller**, which provides Wi-Fi connectivity, GPIO expandability, and sufficient processing capability to manage multiple analog and digital inputs. The **Raspberry Pi 4** complements this by handling higher-level tasks such as camera streaming and image processing without overloading the main controller.

Environmental data is gathered using a **capacitive soil moisture sensor** and an **ambient light sensor**, both offering stable, low-noise readings crucial for accurate plant-care decisions. Actuation is managed through a **mini submersible water pump** connected via a relay driver board, and an **LED grow light** that supplements natural lighting when ambient levels fall below threshold. A **USB camera** mounted near the plant provides real-time imaging for monitoring and computer-vision analysis.

All modules receive regulated power from a dedicated **power supply board**, which steps down a 12 V input to stable 5 V and 3.3 V rails using linear and switching regulators. This modular approach ensures electrical isolation, ease of debugging, and adaptability for future multi-plant expansions.

A. MCU

GreenSync employs a dual-board architecture utilizing both the ESP32 microcontroller and the Raspberry Pi 4 Model B. The ESP32 functions as the system's primary controller, managing soil moisture and light sensing, operating the water pump and grow light, and communicating with the mobile application over Wi-Fi. Its low power consumption, integrated wireless interfaces, and real-time control capability make it ideal for continuous environmental monitoring. The Raspberry Pi 4 Model B complements this by handling high-bandwidth tasks such as high-resolution image capture, livestreaming, and computer-vision processing. This division of labor enables efficient control, data handling, and scalability while maintaining low system cost and power usage. [2][4]

B. Moisture Sensor

The AITRIP Capacitive Soil Moisture Sensor was chosen for its accuracy, durability, and corrosion resistance. Unlike resistive probes that degrade over time, the capacitive design measures changes in dielectric permittivity, producing a stable analog voltage proportional to soil moisture. The sensor operates at 3.3 V or 5 V and interfaces directly with the ESP32's ADC, providing fast, noise-resistant feedback for irrigation control. This design enables long-term reliability with minimal maintenance, ensuring precise soil hydration management across varying environmental conditions. [1]

C. Water Pump

GreenSync utilizes a compact 5 V submersible water pump sourced from the ALAMSCN Automatic Irrigation Kit. This pump was selected for its simplicity, affordability, and compatibility with low-voltage microcontroller systems. The pump operates quietly and delivers sufficient flow for single-plant watering applications, drawing water from a small reservoir through flexible vinyl tubing. It is controlled via a relay module driven by the ESP32, enabling automated irrigation based on real-time soil moisture readings. Its lightweight construction and low power consumption make it ideal for continuous operation in compact smart gardening systems. While not intended for high-pressure applications, the pump provides reliable, consistent water delivery suitable for GreenSync's small-scale irrigation needs.

D. Light Sensor

The VEML7700 digital ambient light sensor measures illumination levels up to 120,000 lux with high accuracy and a wide dynamic range. Communicating with the ESP32 over the I²C bus, it provides lux readings used to regulate the LED grow light in real time. Compared with alternatives such as the BH1750 or TSL2591, the VEML7700 offers superior sensitivity and simpler integration at a lower cost. Its low power consumption and built-in temperature compensation ensure stable readings, allowing the GreenSync system to maintain optimal light levels efficiently. [3]

E. LED Grow Light

The Roleadro 45 W LED Grow Light Panel was selected for its balanced performance, cost, and compact design. Delivering full-spectrum illumination suitable for all stages of plant growth, it provides sufficient intensity for indoor vegetation while maintaining energy efficiency. Controlled through the ESP32, the light activates automatically when the VEML7700 detects inadequate ambient lighting. Although the panel lacks native dimming control, external relay-based automation compensates for this limitation. Its affordability and reliable spectral output make it an optimal lighting solution for a single-plant smart garden.

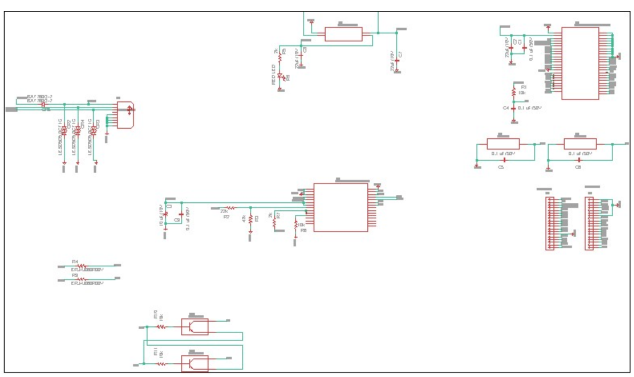
F. Camera

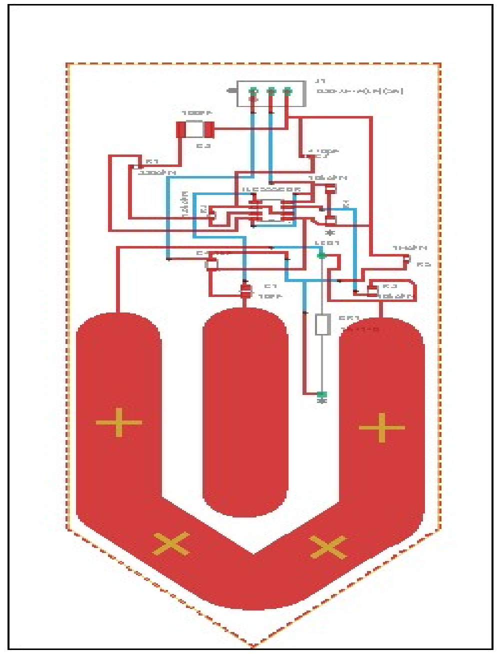
The ESP32-CAM module integrates a 2 MP OV2640 camera with onboard processing and Wi-Fi connectivity, providing a compact and cost-effective imaging solution. It allows GreenSync to capture and transmit plant images without requiring additional networking components. The module supports optional microSD storage and integrates seamlessly with the system's Raspberry Pi for advanced image analysis. While its resolution is modest, it is sufficient for visual growth monitoring and status updates, aligning with GreenSync's goal of combining affordability, simplicity, and functionality in a compact form factor. [5]

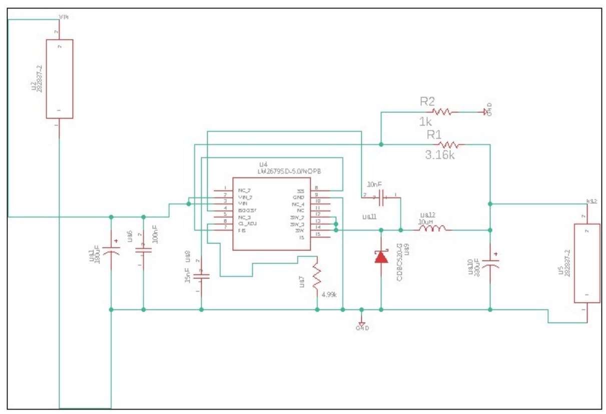
G. Enclosure

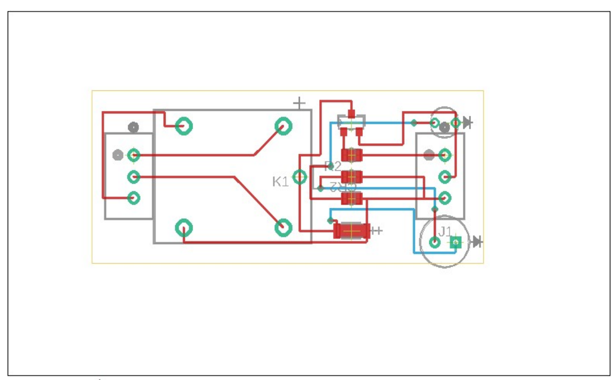
The Viagrow Extra Strength Propagation Seed Starter Tray with Tall Dome was selected as the enclosure for the GreenSync system due to its durability, visibility, and suitability for controlled indoor plant growth. The clear polycarbonate dome provides ample vertical space for plant development while maintaining a stable, enclosed microenvironment that helps regulate humidity and temperature. Its transparency allows consistent light exposure and enables the integrated camera to monitor plant health without obstruction. The tray base securely houses the soil pot, sensors, and irrigation tubing, while the rear section accommodates the mounted PCBs, pump, and cable routing. This configuration maintains a clean layout and simplifies maintenance and sensor access. The Viagrow tray's modular and reusable design also supports scalability for future multi-plant or extended test configurations.

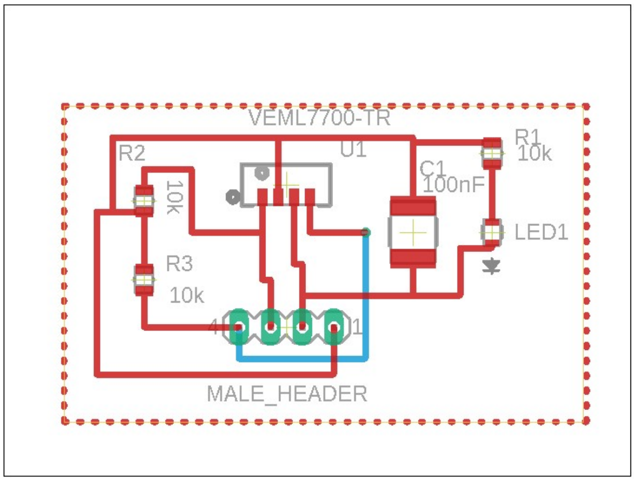
IV. HARDWARE TECHNICAL DESIGN

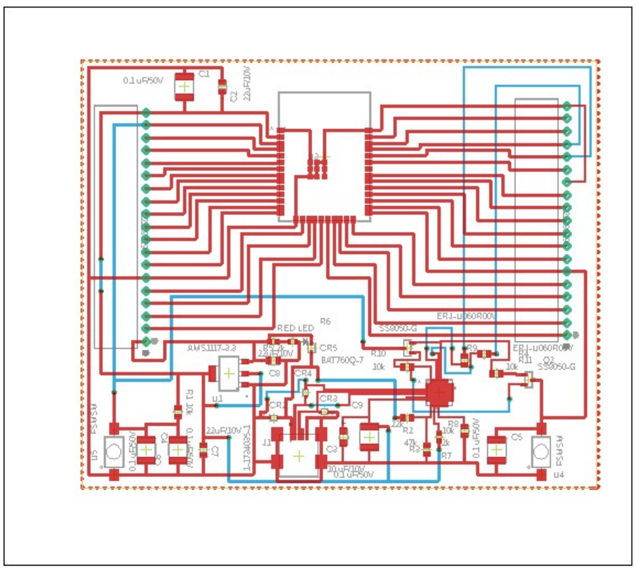


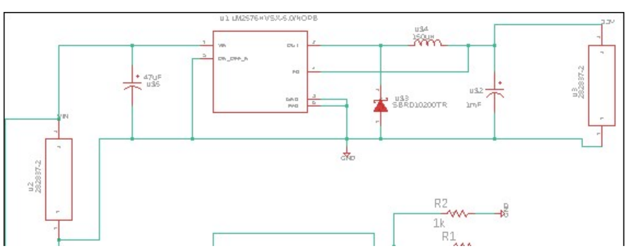


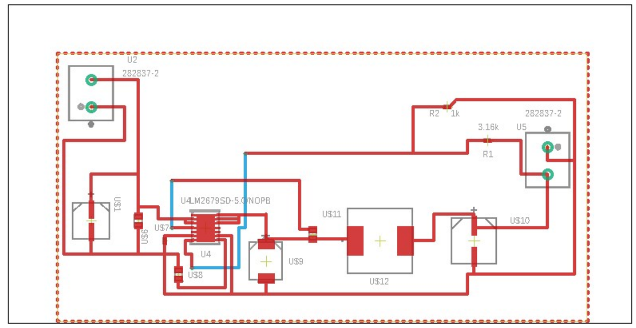


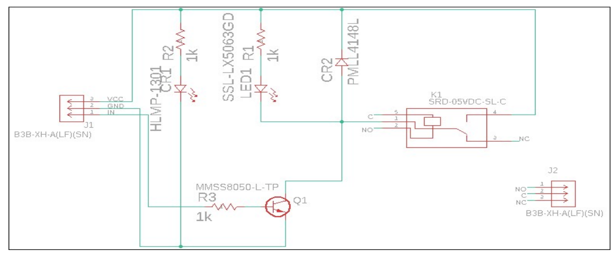












V. SOFTWARE DESIGN

The GreenSync software architecture unifies embedded firmware, communication protocols, and a mobile application into a seamless automation platform. The system follows a modular hierarchy composed of sensor-node firmware, a central-control algorithm on the ESP32, and a user-facing mobile app connected through MQTT.

The **GreenSync mobile app** is developed in **Flutter**, enabling cross-platform deployment for Android and iOS. Figma prototypes guided the design of an intuitive, data-rich user interface. The main dashboard displays each registered plant as an interactive icon surrounded by dynamic status rings indicating soil-moisture and light exposure levels.

Tapping an icon opens a detailed control page with live readings, historical charts, and manual override toggles for watering and lighting. Additional menus—such as *Settings* and *User Profile*—are accessible via a navigation drawer, keeping the main screen uncluttered. Push notifications are reserved for critical alerts (e.g., low reservoir level) to avoid overwhelming users.

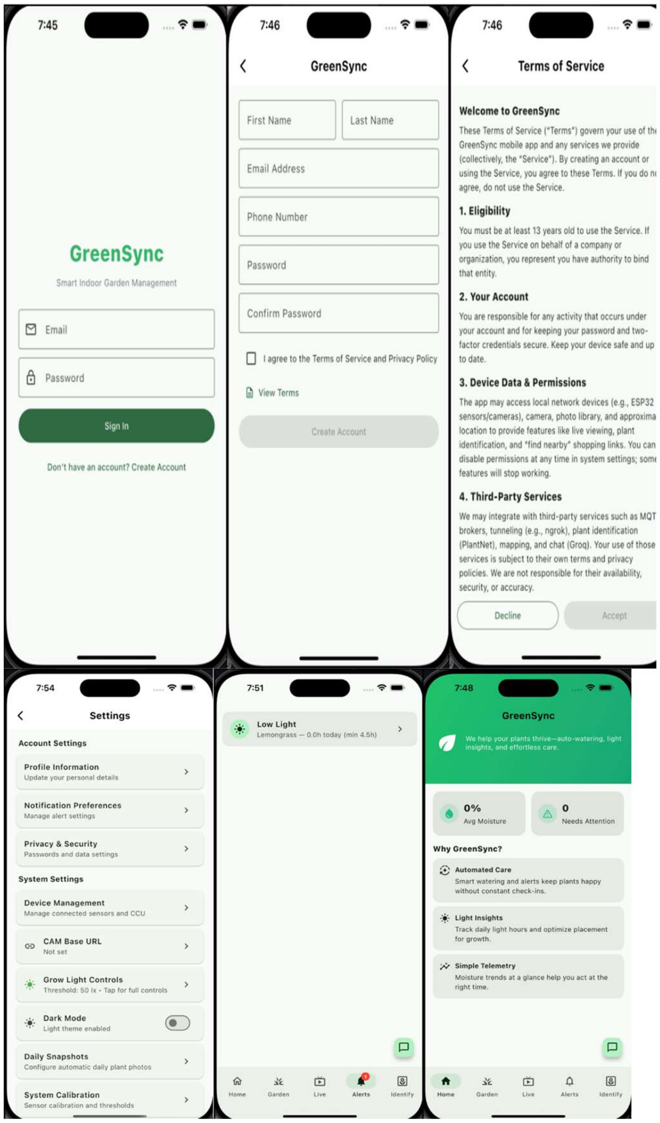


Fig. .(top) and Fig..(bottom) User Login, User Signup, Terms of Service, User Settings, User Notifications, and Dashboard, respectively

The GreenSync app has a **two-factor authentication (2FA)** setup prompt that appears when signing into an online account. The message encourages users to add an extra layer of security by using an authenticator app—such as **Google Authenticator** or **Authy**—to protect their login credentials. Enabling 2FA means that even if someone steals the user's password, they would still need the time-sensitive code from your phone to gain access. The two buttons, "Later" and "Set up now," allow users to either postpone or immediately configure this additional protection step.

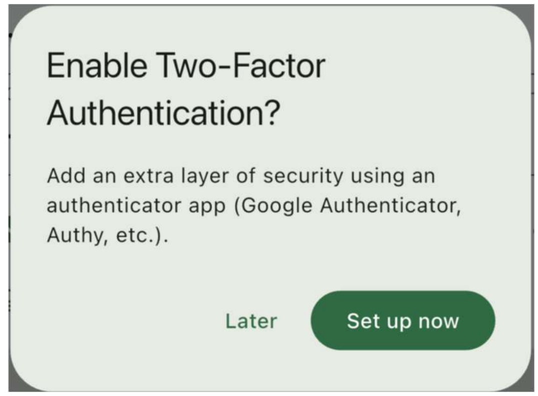
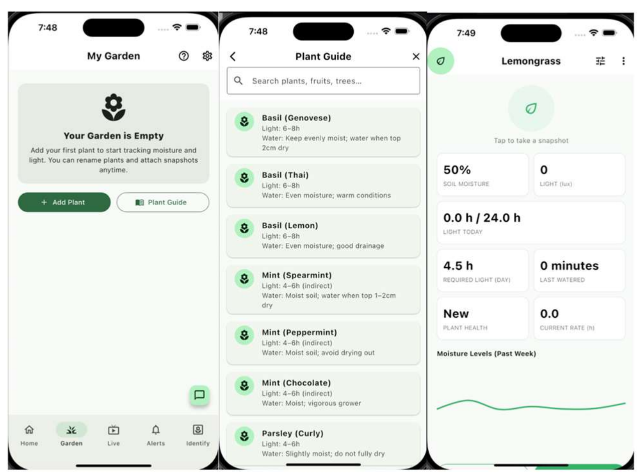


Fig. Prompt to enable two-factor authentication for added account security

The **GreenSync mobile application** provides an integrated platform for monitoring and managing automated plant care. Its clean dashboard displays the user's garden and enables quick plant registration, while the built-in **Plant Guide** offers curated care instructions such as light duration, watering frequency, and moisture preferences. Each plant's dedicated **PlantCard** consolidates real-time sensor data, including soil moisture, ambient light, and recent watering activity, allowing users to track environmental conditions at a glance. The **Plant Settings** menu grants fine control over moisture thresholds, light requirements, and automatic watering parameters, supported by an in-app **Help section** that explains each setting clearly. Users can also customize alert preferences for soil dryness, low-light conditions, or weekly summaries, creating a smart and adaptive system that promotes consistent plant health with minimal user intervention.



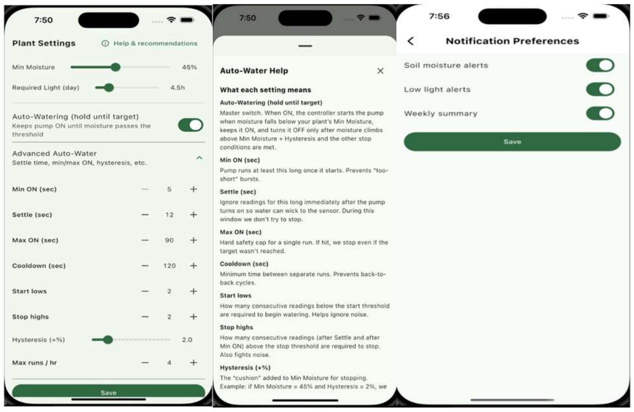
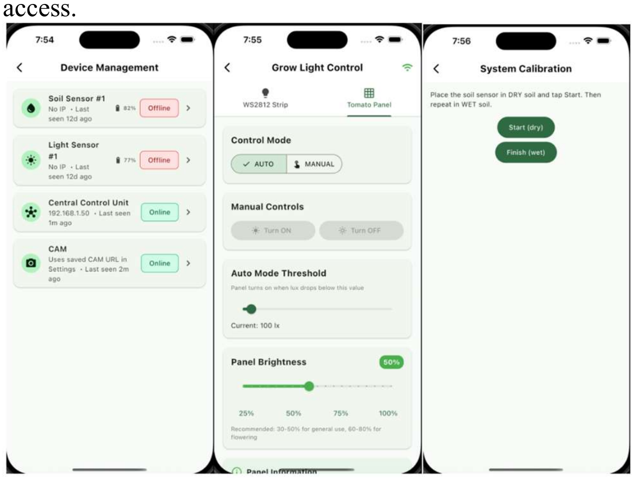


Fig. 6 (top) and Fig. 7 (bottom) — My Garden view, Plant Guide, PlantCard with sensor readings, Plant Settings and Water Pump Controls, Auto-Water Help Guide, and User Notification Preferences, respectively.

The **GreenSync mobile platform** extends beyond plant monitoring to provide complete system management and customization. The **Device Management** screen displays the operational status of each connected module—including soil and light sensors, the central control unit, and camera—allowing users to verify connectivity, battery levels, and last-seen timestamps at a glance. The **Grow Light Control** tab gives precise manual or automatic adjustment of brightness and lux thresholds, ensuring plants receive ideal illumination for their growth stage. Through the **System Calibration** interface, users can easily fine-tune soil moisture sensors by recording reference points in dry and wet conditions. The **Privacy & Security** menu reinforces data protection by supporting password changes, anonymous telemetry, and biometric sign-in options. A built-in **Dark Mode** provides a visually comfortable interface for low-light environments, while the **My Garden** dashboard supports multiple plant cards, summarizing the status of each plant for quick, organized access.



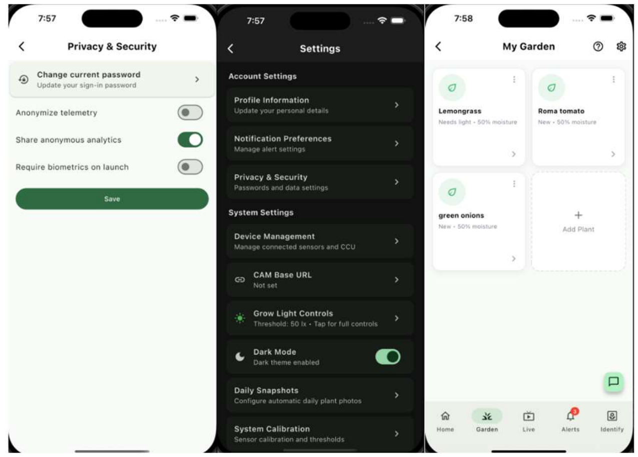
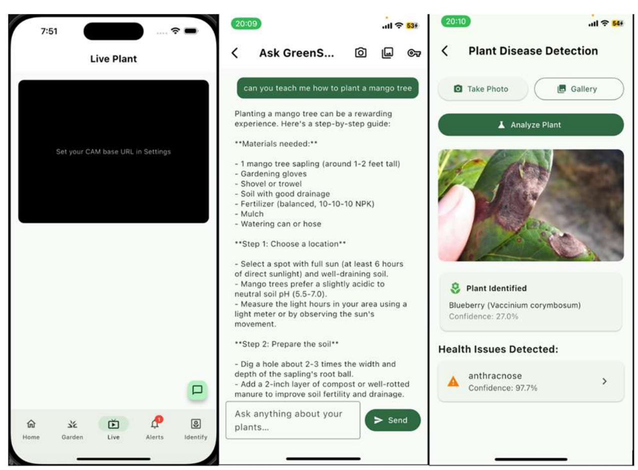


Fig. (top) and Fig. (bottom) — Device Management, Grow Light Control, Moisture Sensor Calibration, Privacy & Security, Dark Mode, and Multi-Plant Garden Dashboard, respectively.

The **advanced feature suite** of the GreenSync mobile application enhances automation, monitoring, and AI-based plant diagnostics. The **Live Plant View** tab integrates camera feeds from the Raspberry Pi or ESP32-CAM, allowing users to observe plants in real time through a live stream interface. The **Ask GreenSync** tab connects to the system's integrated **Groq API**, enabling a conversational assistant that answers user queries about plant care, device setup, and troubleshooting. For intelligent analysis, the **Plant Disease Detection** module uses computer vision to identify plant species and detect leaf diseases such as anthracnose, providing detailed treatment recommendations. The **Analyze Plant** tab extends this capability by allowing users to upload or capture photos for identification and health assessment, while the **Live Detection** mode utilizes the **YOLOv8** model for real-time recognition of plants and potential issues. Together, these features create an AI-augmented ecosystem that merges automation, visual monitoring, and plant health intelligence into one cohesive platform.



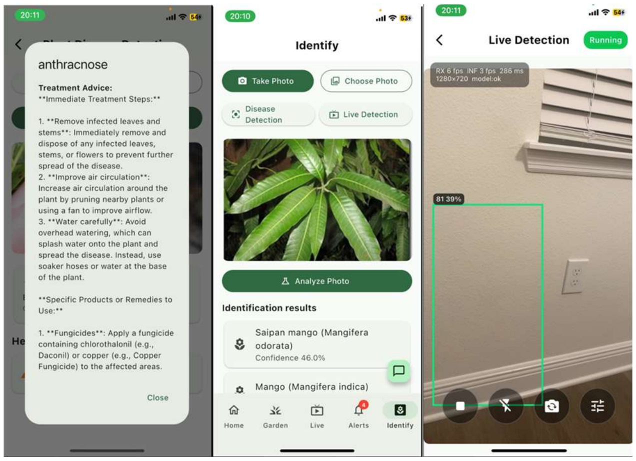


Fig. (top) and Fig. (bottom) — Live Camera Plant View, Ask GreenSync AI Chat Interface, Disease Detection, Disease Treatment Recommendations, Plant Analysis, and Live Detection using YOLOv8, respectively.

This screenshot below shows raw sensor data being streamed from the Arduino IDE, during testing or calibration. Each line represents a data packet containing real-time environmental readings such as soil moisture (moisture and moisture_raw), voltage (mv), and light intensity (lux). The consistent numeric values demonstrate stable sensor operation and successful serial or MQTT data transmission between the ESP32 controller and connected sensors. This output is used for debugging, calibration verification, and ensuring data accuracy before integrating the readings into the mobile app's live dashboard.


```
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Fig. 12 — Real-time sensor output showing soil-moisture, voltage, and light readings streamed from the Arduino IDE.

VI. Conclusion

The GreenSync system provides an intelligent, low-maintenance approach to indoor plant care by integrating environmental sensing, automated control, and real-time monitoring. Through the use of an ESP32 microcontroller and Raspberry Pi 4, the system efficiently manages watering, lighting, and visual feedback while maintaining a compact and affordable design. Its combination of capacitive moisture sensing, ambient light detection, and live camera monitoring ensures accurate environmental regulation with minimal user effort. The companion mobile application enhances accessibility by offering real-time data visualization, plant recognition, and AI-based health assistance. Designed with scalability and reliability in mind, GreenSync demonstrates how modern embedded systems can simplify sustainable plant maintenance within smart home environments.

VIII. ACKNOWLEDGEMENTS

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