

AquaFlora Smart Terrarium: A Self-Sustaining Internet of Things (IoT)-based Terrarium for Smart Ecosystem Management

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Abstract— Using Internet of Things (IoT) technology in smart terrariums is a growing trend that aligns with the move towards more automated and better- well-managed ecosystem gardening. AquaFlora Smart Terrarium is a state-of-the-art system designed to create and maintain the perfect environment for various plants. It features a network of sensors, actuators, and electronic components, all orchestrated by an ESP32 microcontroller. The system leverages four actuators to control light, humidity, irrigation, and cooling, ensuring optimal conditions for plant growth. Three sensors, which are the Capacitive Soil Moisture Sensor, DHT22, and BH1750FVI to monitor soil moisture, temperature, humidity, and light intensity, providing real-time data to the microcontroller. The terrarium can be conveniently controlled via a mobile app and Node-RED, allowing for remote monitoring, control, and automation through Firebase and MQTT. Node-RED visualization of sensor data over a 10-hour period demonstrated the effectiveness of the automatic mode in maintaining stable plant conditions. Soil moisture remained above 60%, temperature ranged between 30.1°C and 33.1°C, humidity between 69.10% and 74.00%, and light intensity between 23 Lux and 175 Lux. The AquaFlora Smart Terrarium represents a significant innovation in plant care, offering a reliable and automated solution to create and sustain the ideal environment for healthy plant growth.

Keywords— Smart terrarium; IoT; ESP32 microcontroller; mobile app; Node-RED; real-time monitoring; automation; plant growth.

I. INTRODUCTION

The integration of Internet of Things (IoT) technology with natural ecosystems has introduced new approaches on ecological issues, allowing for more innovative and data-driven approaches to ecosystem management. For instance, IoT crowdfunding platforms have become essential in financing projects that leverage IoT technologies for various applications, including smart gardening solutions such as Smart IoT Terrarium. Previously, people used these terrariums to establish controlled ecosystems, aiding in the protection of small animals and the growth of plants. These microsystems were humans' answers to nature, as well as works of art in the form of personal miniatures[1].

Thus, these technologies allowed for the integration of self-expression tools with science and art. However, their long-term sustainability potential was limited due to the need for human control and the difficulty in creating the ideal environment, particularly for ecological research and biodiversity preservation. IoT technologies offer a transformative response to these limitations by automating and monitoring critical environmental factors with real-time measurements. The integration of IoT in gardening allows for real-time monitoring and management of environmental conditions, which is crucial for the successful cultivation of plants in a controlled setting. The sensors regularly record environmental factors such as soil moisture, light intensity, temperature, and humidity to control the environment. The terrarium adapts the living conditions to optimize plant and animal wellness as minimally as possible. Furthermore, through this innovation, researchers can observe and study different species interactions in enclosed environments and gain a better understanding of ecosystem functioning. On balance, this also enhances the health of the ecosystem through automation and a higher level of control, which protects species, improves domestic gardening, and helps sustain biodiversity[2], [3], [4], [5].

The Smart IoT Terrarium is a significant contribution to environmental conservation, animal well-being, green design, and science and technology[6], [7]. It creates rich natural environments in dense urban buildings, promotes responsible pet treatment, and serves as an educational tool, attracting people to protect biodiversity and sustainable life in urbanized and digital spaces. Integrating IoT technologies into these terrariums boosts their functionality while supporting sustainability and environmental care.

A. Literature Review

The concept of the IoT is bringing about significant transformations in the sphere of home automation, providing facilities for achieving the highest level of control and optimization in such areas as terrariums. Stanciu, Bogdan, and Marcu offer a Smart Terrarium as a tool for implementing home automation via IoT[8]. This device enables the regulation of environmental parameters and uses a great number of communication technologies specific to the IoT. The authors prove that this solution helps substantially improve the quality of user experience, allowing to control and monitor a terrarium

remotely. Nevertheless, they claim that combining so many devices and technologies to reach the highest performance level is a challenging task.

The study by Kumar S, Azariah J, and Jenita T explores the potential of plants to improve indoor environment quality using a low-cost embedded system using an Arduino Uno for air monitoring and irrigation control[9]. This research reveals the health benefits of improved indoor air and the aesthetic and functional uses of terrariums in interior design. Ayushi Trivedi and Nirjharnee Nandeh's research on smart farming shows that similar technologies can create better environmental conditions for terrariums[10]. The study also highlights the significant contribution of IoT and AI technologies to agriculture and smart terrariums. Garg and Alam emphasize the importance of AI, cloud computing, and big data in developing smart agriculture systems and improving terrarium ecosystems[11].

The literature related to sensor selection in smart terrariums demonstrates a significant contribution of various sensing technologies in improving environmental conditions and ensuring plant health. Thinura et al. had implemented real-time notifications and safety systems in garden monitoring systems in which Blynk application, temperature & humidity sensor and colour sensor were used[12]. This fact indicates the importance of following the changing environment in terrariums to sustain the best environment for plant growth. At the same time, Abu et al. focus on improved water and energy use in indoor plants systems and apply soil moisture and light-dependent resistive sensors to keep the best water flow and light exposure[13]. Thus, both these sources prove the necessity of relevant sensors to ensure optimal growth in smart terrariums and indoor plants systems.

The DHT22 sensor is a cheap and reliable way of measuring the level of temperature and humidity. According to Wardani et al., it has minimum error rate as well as accuracy in measuring greenhouse temperature and humidity[14]. These benefits make it perfect for the use in smart terrarium systems. Azhari and Nasution have also measured the precision of DHT22, stating that it provides consistency in the environment[15]. Moreover, DHT22 works with widely used microcontrollers, such as Arduino, which allows for easy integration into smart terrarium systems. Overall, the utilization of DHT22 in the system enables both professionals and novice creators to have cheap and reliable instrumental to maintain the microclimate[16].

The use of the capacitive soil moisture sensor is the vital aspect of terrarium irrigation. The sensor's precision and accuracy, which would be beneficial for determining the appropriate water level and preserving plants' health, were discussed by Majumder and Kasirao[17]. Their calibration can be optimized for terrarium requirements, for example, by amending it to produce the best results for sloping soil, as Majumder and Kasirao, and Placidi and Gasperini, proposed[18]. BH1750FVI sensor is shown to be more accurate in determining light intensity which is mandatory for terrarium maintenance. This sensor accuracy was discussed by Siepert Bryan to monitor light intensity in terrariums in real time[19], [20].

II. THE MATERIALS AND METHOD

The ESP32 Devkit V1 microcontroller [21] (the block diagram is shown in Fig.1) is a critical component of the Smart IoT Terrarium as it provides built-in wireless capabilities and robust computational performance. Being endowed with an extensive set of GPIO pins, built-in Wi-Fi, Bluetooth, and dual-core processing, the development board is particularly useful in the current project due to the ability to manage dozens of sensors and devices not only within the terrarium but also during experiments outside[22], [23].

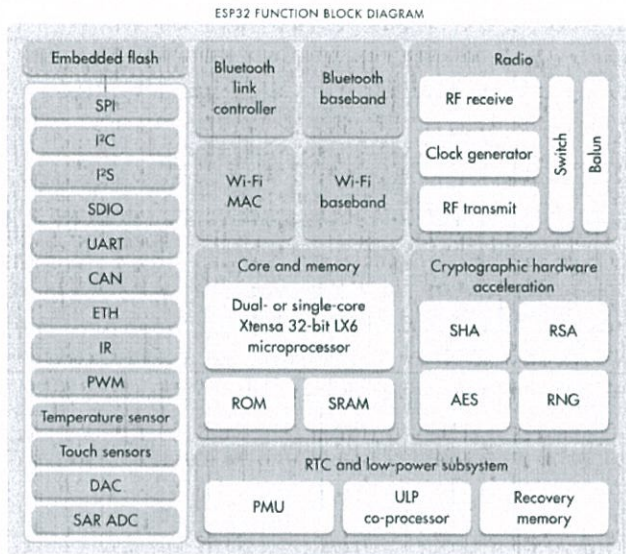


Fig. 1 ESP32 Block Diagram [24]

Moreover, the board can connect to a variety of communication protocols, including I2C, SPI, and UART, meaning that multiple components and sensors can be connected[25]. In the future, it can be deemed essential for the operation of the gear required for remote or outside experiments.

This project uses a several components to monitor the terrarium's environment and ensure proper operation. The BH1750FVI Digital Light Intensity Sensor, DHT22 Temperature and Humidity Sensor, and Capacitive Soil Moisture Sensor are used to monitor soil moisture, temperature, humidity, and light intensity. The microcontroller processes the data and makes real-time changes to maintain the terrarium's perfect state. The 4-Channel Relay Module controls the 12V LED bulb, 12V DC fan, and 5V mist maker. A reliable power management system is integrated to support the operation of the system.

The Breadboard Power Module MD-102 minimizes power failures and provides consistent measurements for low-power devices[26]. An extra 12V water pump and jumper wires facilitate water flow. This system ensures the terrarium's maintenance and biodiversity sustainability.

A. Flow Chart

The Smart Terrarium's operational flowchart, as illustrated in Fig. 2, presents three modes of operation that are designed to facilitate improved user control and environmental automation. The users are provided with manual mode to

control the actuators of the terrarium. This allows them to make immediate changes to the lighting, ventilation, and watering systems according to their preferences or an urgent request.

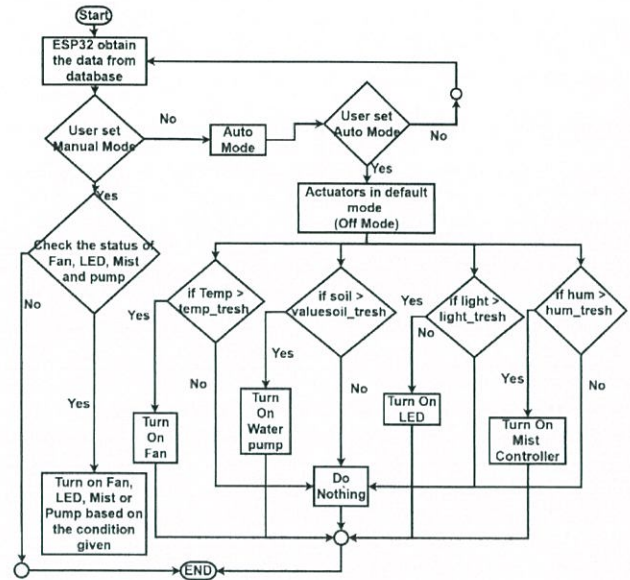


Fig. 2 Smart Terrarium's operational flowchart

On the other hand, in the Auto mode the terrarium's environment is controlled by equipment that is supervised by real-time input from sensors. This mode does not require constant human input and ensures that the state of the terrarium is optimal. The current mode exercises the terrarium's watering system, turns on fans, and adjusts its lighting to provide the best environment to its inhabitants. Finally, the third mode is Monitoring, and it allows users continuous oversight of the situation to ensure that the equipment is functioning, and the parameters are fine.

The convenient graphical interface that is available either locally or remotely allows switching between these modes and ensures their simplicity. The mode significantly simplifies terrarium's administration and creates a basis for future improvements, such as the ability to use prediction analytics with greater efficiency as sensors and modelling improve.

B. Scientific Block Diagram

The smart terrarium project's scientific block diagram shown in Fig.3 outlines its structure and operation, with the ESP32 microcontroller acting as a central component.

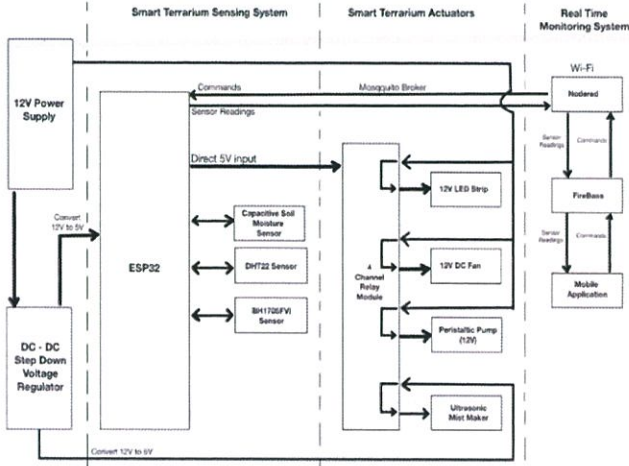


Fig. 3 Scientific Block Diagram

As mentioned in the scientific block diagram (Fig. 3), DHT22 for temperature and humidity measurement, BH1750FVI for light intensity, and capacitive soil moisture sensor to measure moisture level of the soil are used. The relay module controls high power devices, including DC fans, LED strips, and a water pump, ensuring system stability and effective energy consumption. The diagram provides a comprehensive understanding of the system's operation and interfaces.

The block diagram of the power management system for the terrarium demonstrates the control and distribution of 12V power supply to components, including the step-down voltage regulator. It also highlights the role of Node-RED in enabling communication between the ESP32 microcontroller and the Firebase cloud platform, allowing continuous monitoring and remote control of the terrarium's environmental conditions. The diagram provides a clear understanding of the smart terrarium's structure and data transmission.

III. RESULTS AND DISCUSSION

A. PCB Designing and Testing

The process of PCB design for the Smart Terrarium was conducted using EasyEDA — a software suite that allows creating electronic schematics, as well as designing printed circuit boards, in a simple and efficient manner[27], [28]. Accordingly, the architecture of the PCB is based on the detailed schematic specifically designed for the ESP32 pin configuration. Notably, it is designed to suit the sensible positioning of terminals, allowing for the convenient connection of various sensors and relay modules, and making it usable and serviceable. The microcontroller is connected to the power supply of 9V, which provides stable energy for all components through the breadboard. Consequently, the required voltage is relatively allocated for each module, ensuring the proper work of each component. The careful design makes the resulting PCB not only a reliable carrier for components but also a tool ensuring their appropriate functioning and powering.

The schematic diagram shown in Fig. 4 is entirely transformed into a multilayer PCB, which uses multiple levels

to facilitate circuit connections and placements and thus ensure a compact design.

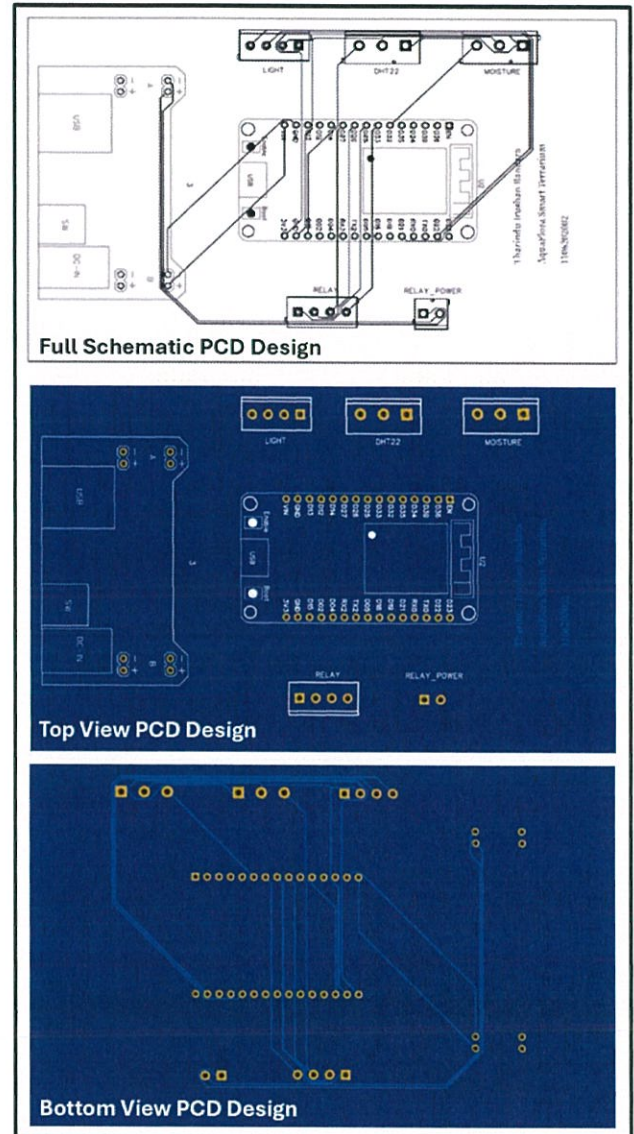


Fig. 4 PCB Schematic Diagram

As a result, all sensors, boards, main modules, and the ESP32, relay module, and the sensors, are positioned exactly corresponding to one another and their connection. Moreover, the PCB is also designed for comfort, making it easy to assemble the overall smart terrarium configuration; thus, top and bottom views are used to represent terminal placement and unambiguous marking. In addition, the cable management is also reflected in reduced wiring, making it more visible and complex under the board. Thus, the resulting PCB meets all requirements of efficient and reliable use for the smart terrarium system.

B. Mobile Application Development

The Dart programming language is designed for building natively compiled applications across mobile platforms. The smart terrarium application as shown in Fig. 7, was created with the use of Flutter, a powerful UI toolkit by Google[29], [30].



Fig. 7 Mobile Application

Through the mobile application, the users can manage and monitor their smart terrariums through an intuitive and visually pleasing interface[31]. The architecture of the application is initiated through the main.dart file. In this main file, the initial setup is defined, allowing the configuration of the local notification systems and Firebase functions. These settings assure that the application is appropriately provided with the ability to handle real-time data and this sends requests for notifications when necessary. Furthermore, the user experience has been enhanced through the incorporation of Material Design. This ensures that the colorful and customizable interface does not only make terrarium a highly functional app but also a highly aesthetically pleasing one.

The application is created to provide convenient navigation and control over the smart terrarium’s capacities. The Navigation module of the app is provided with a bottom navigation bar to help a user move easily between the critical elements that include Camera, Manual Mode, and Auto Mode. The users should not experience difficulties monitoring and adjusting the terrarium’s environmental parameters since the interface is simple in both modes. For instance, the settings on the Auto Mode page are linked with the Firebase Realtime Database, which helps the terrarium’s conditions to be updated while the based-on sensor data. Consequently, the users do not have to monitor the terrarium’s state continuously since the connectivity allows automatic corrections and adjustments. The Manual Mode page allows a user to monitor the conditions and control the fan, LED lights, system of fog, and a pump. This information is important for a user to know how to alter the settings and requirements if needed. Besides, the InfoPage is designed to provide users with detailed information about the AquaFlora system to help the app be user-centred and involve all the needed characteristics.

C. Integration Testing

1) Auto Mode

The Smart Terrarium System’s Auto Mode as shown in Fig. 8, is an advanced environmental control system that uses sensors to regulate the terrarium environment based on real-time outcomes. The ESP32 microcontroller monitors light,

temperature, humidity, and soil moisture, and when implemented in Auto Mode, actuators like fans, LED lights, pumps, and humidifiers are dispatched based on these outcomes and specific thresholds. For example, LED lights are automatically dispatched when light exposure is below a specific lux value, and cooling fans and humidifiers are distributed when temperature and humidity are adjusted. Pre-defined thresholds for soil moisture (60%), humidity (90%), light intensity (50 Lux), and temperature (31°C) were applied for optimum condition, based on data from previous smart terrarium projects[32], [33], [34], [35].

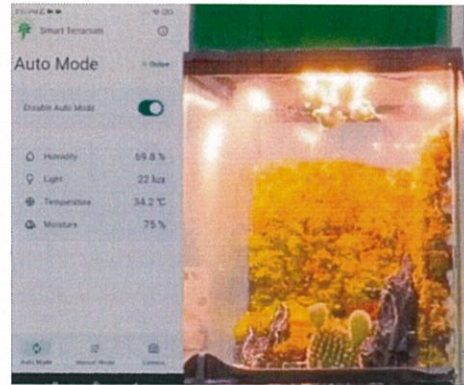


Fig. 8 Auto Mode

The operating principle of the Auto Mode of the Smart Terrarium is based on the connection between the mobile application, Firebase, and Node-RED. The system works by sending the commands to Node-RED, where the terrarium’s environment is monitored and managed. In the meantime, the mobile application’s dashboard interface is updated. Thus, users can control the terrarium’s settings from a remote location. The system’s operational mode is triggered by the callback function, whereas sensors and commands are employed to adjust the ESP32’s actuators. In the end, the interconnection between systems serves to keep the plant’s environment in check.

2) Manual Mode

As shown in Fig. 9, the smart terrarium system based on the ESP32 allows direct user manipulation of several environmental conditions in Manual Mode, as commands are sent from Node-RED through the MQTT (MQ Telemetry Transport) protocol. The ESP32 uses a callback function to read the provided MQTT messages, making it possible to determine which of the system’s actuators is being addressed, such as the fan, light, pump, and humidifier. Subsequently, after receiving the relevant commands, the ESP32 function alternates the GPIO ports, which leads to the appropriate changes.

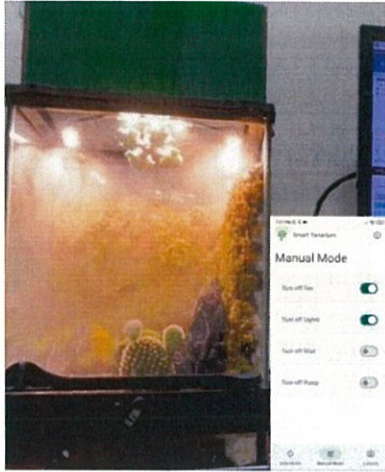


Fig. 9 Manual Mode

For instance, if a message is received that orders the device to initialize the fan, then the ESP32 will respond by setting the pin to an 'ON' state. Thus, this particular function allows the current mode of the terrarium to be directly controlled by users, ensuring that every component can be specifically manipulated. At the same time, Node-RED will act as an intermediary in this situation, making certain that the commands are executed as intended as it will represent the process with which the users interact on its interface.

To implement manual control of a terrarium's environment, we integrated the ESP32, Node-RED, and Firebase as shown in Fig. 10. A command is sent from the mobile application to Node-RED through Firebase, which executes and displays it on its dashboard. The ESP32 changes the actuator based on the environment, which entails temperature and humidity by DHT22 sensor and light intensity by the BH1750FVI sensor.

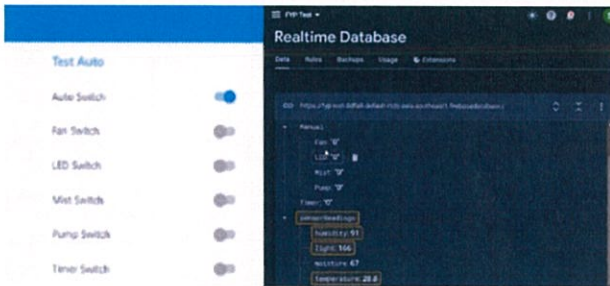


Fig. 10 Node-RED and Firebase

Moreover, the ESP32 adjusts the illumination, moisture, and humidity by a relay driver or a micro grid mist. The manual control of a terrarium's environment is successfully implemented ensuring exact execution and display that provides the user with complete control over the terrarium.

D. Water Retention and Plant Health in Smart Terrarium vs Control

A 10-day test was applied to the IoT smart terrarium to verify whether the technology employed provides better water retention and plant health when compared to the standard control environment. Since the terrarium is designed to sustain

acceptable moisture ranges, the plants do not have to be irrigated frequently. This attribution is denoted by the integrated layered materials in the soil mix to include lava rocks[36].

Day 01



Original Image

Green Intensity

Mean Intensity = 27.145

Day 10



Original Image

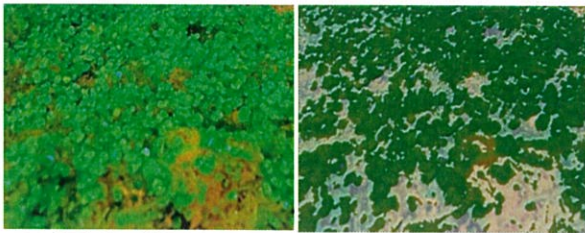
Green Intensity

Mean Intensity = 96.36

Fig. 11 Mean Intensity of the terrarium in controlled environment (Day 1 to Day 10)

The Fig. 11 illustrates that there is a notable difference in the plant health at the initial and final conditions of the control environment over ten days where the plant is watered once in every seven days and received light during daytime only. Due to the lack of an effective water retention feature in the images recorded and shown below, there is an inherent deterioration of the control environment. As indicated, white portions show areas colour burnt or plant deaths. This indicates the challenge of maintaining the health of the plants without the advanced environmental condition provision by the terrarium. The difference between the early and later phases of plant health in the control environment indicates the importance of an appropriate environmental control and effective water retention.

Day 01

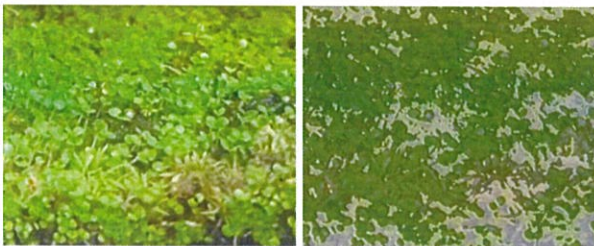


Original Image

Green Intensity

Mean Intensity = 66.935

Day 10



Original Image

Green Intensity

Mean Intensity = 68.507

Fig. 12 Mean Intensity of the terrarium in stable environment (Day 1 to Day 10)

Fig. 12 displays the smart terrarium's ability to maintain stable environmental conditions and take care of plant health better than the conventional control design. The terrarium was able to regulate moisture, temperature, intensity of light, humidity for ten days, showing the same mean intensity value of the green colour. The control environment kept for irregular irrigations showed a significant adverse impact on plant vitality within these days. The mean intensity value was 68.176 in ten days. On the other hand, the best mean intensity for the control environment was 27.145, and the worst is 135.397. The results indicate that the smart design of the terrarium based on the substrate with different moisture and man-made environmental controls is well-functioning for ongoing plant growth. It is not surprising that the smart terrarium design can keep the optimal healthy plant growing without regular watering. It is advantageous as its innovation supports plant vitality in various conditions within a minimal time and maintenance for the users who may not possess the proficiency to regulate plant health.

The smart terrarium is evidently efficient in comparison to other terrarium designs[33], [34]. It can be feasible within real-time monitoring. It is a convenient and effective version for educational and researching purposes in educational institutions or residential and commercial settings. The overall conclusion seems to be certain that the smart terrarium is a reliable and revolutionary type of design to maintain plant life perfectly.

E. Usability Testing

Fig. 13 presents the Node-RED dashboard, which serves as the central control hub for the smart terrarium. Users can interact with the dashboard to select different modes of operation, influencing how the terrarium's actuators function. Alongside this, real-time and historical data for crucial environmental factors like humidity, temperature, soil moisture, and light intensity are visually represented through line charts, offering insights into the terrarium's conditions. This comprehensive interface facilitates effective monitoring and management of the smart terrarium, ensuring optimal conditions for the plants within.



Fig. 13 Node-Red Dashboard including line charts of each environmental factor

The smart terrarium's effectiveness in maintaining an optimal environment was analyzed over a 10-hour period in auto mode. Pre-defined thresholds for soil moisture (60%), humidity (90%), light intensity (50 Lux), and temperature (31°C) were applied for optimum condition, based on data from previous smart terrarium projects.

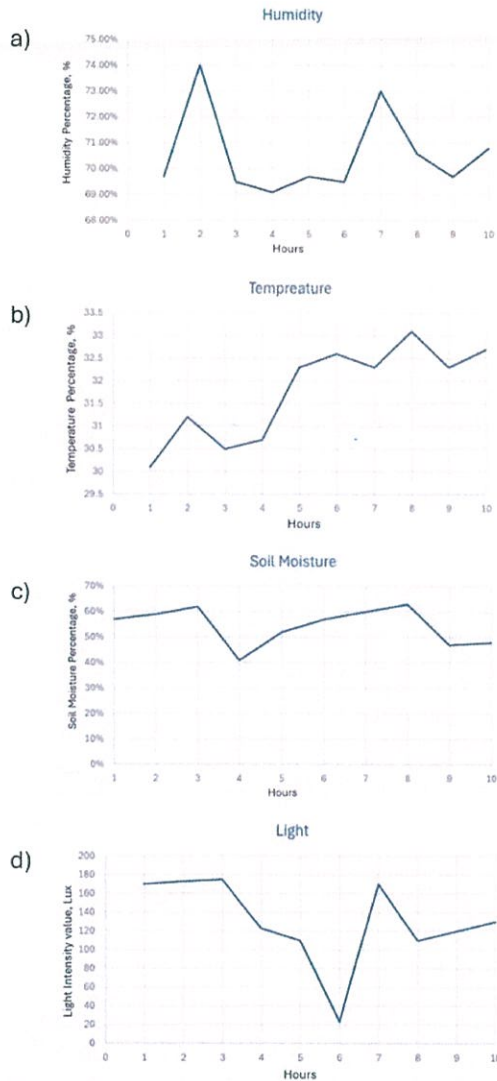


Fig. 14 The sensor readings over a ten-hour period for a) Humidity percentage, b) Soil moisture percentage, c) Temperature and d) light intensity value.

Sensor data visualized in Fig. 14. reveals the system's responsiveness to environmental fluctuations. In Fig. 14.a, the humidity remained below the 90% threshold throughout, indicating no humidifier activation. The cooling fan engaged once in the first four hours and then continuously thereafter, as the temperature exceeded 31°C shown in Fig. 14.b.

Soil moisture readings in Fig. 14.c is above 60% triggered the water pump twice, demonstrating the system's ability to address insufficient moisture levels. Light intensity shown in Fig. 14.d dropped below 50 Lux only once, activating the light strips, showcasing energy efficiency while ensuring adequate illumination.

Overall, the observations highlight the smart terrarium's successful autonomous operation in maintaining desired environmental conditions, adjusting actuators based on sensor data and pre-set thresholds.

The monitoring data provided from the AquaFlora Smart Terrarium are indicative of the effectiveness of the automated control system. Particularly, the environmental constraints were regulated by the system automatically, in response to gathered readings. The most optimal soil moisture,

the temperature and humidity profile, as well as the light levels, were maintained by the automatic activation of the system's fan, pump, and lights. The observation should be made in the context of the automatic mode of the system, support which presupposes that the actual controlling actions, i.e. opening the water pump or adjusting the temperature settings, were performed by the AquaFlora system independently. In manual mode, conversely, the user interface offers controls over the given parameters, to do this manually.

IV. CONCLUSION

The prototype representing a smart terrarium that provides holistic control over environment conditions is one of the most vivid examples of how the IoT technology's recent advances changed the way this type of facility works. A specialized terrarium supports a wide range of plant and animal species through controlling the levels of temperature, humidity, soil moisture, and lighting. These processes are monitored and regulated via powerful microcontrollers, IoT sensors, and actuators. It is important that such system design allows for the automated control of the environment as it proactively integrates monitoring and automated adjustment. In this way, while ensuring the proper conditions, the system also supports the notion of biodiversity and ethically resists pet management. The prototype should be highly favored by those committed to sustainable habitat management as its IoT advanced technology and real-time data management ensure the habitat's self-sustainability.

The Smart Terrarium could benefit from integrating a camera module to provide live video feeds, improving monitoring capabilities and enabling remote access to real-time visual data. This would hence help the users to ensure perfect environmental conditions for plant and animal well-being. Meanwhile, Artificial Intelligence (AI) technology would give additional insight concerning plants' health tracking, hence making it possible for more precise management of the condition. The feedback mechanism based on the activity of plants analyzed by camera could hence refine the operation of the terrarium to maintain perfect conditions as far as is feasible. The AI-simulated terrarium could also provide early warning of possible future operation which the AI could try to simulate or bypass to maintain the ideal environmental condition[37], [38], [39].

In addition, as more IoT devices connect to each other, the potential for security threats correspondingly increases. Implementing robust cyber security measures within the Smart IoT Terrarium is important to safeguard sensitive information and enhance user confidence in the system. For instance, in the absence of adequate security, an attacker could potentially gain unauthorized control over the terrarium's settings, leading to disruptions such as altering light levels or humidity conditions. Tawalbeh et al. thoroughly explore the privacy and security challenges in IoT systems by highlighting key issues such as insufficient device updates, lack of strong security protocols, and user ignorance as significant vulnerabilities[40]. To mitigate such risks, future advancements should prioritize the integration of comprehensive security features and protocols designed to protect user data and prevent unauthorized access to the IoT-enabled smart terrarium.

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