Optimizing Water Use in Gardening Through an IoT-Based Autonomous Irrigation System

M. H. H. Muhammad Zaidi[1], K. L. Chua[1], X. Y. Yap[2], K. S. Chia[1,*]
[1]Faculty of Electrical and Electronic Engineering. Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Malaysia
[2]MERRY Electronics (S) Pte. Ltd, 658065, Singapore
[*]corresponding author's email: kschia@uthm.edu.my

Abstract –*This study focuses on improving water conservation in plant maintenance by creating an intelligent, automated irrigation system powered by Internet of Things (IoT) technology. Its key goals include designing an IoT-based watering system, developing a mobile application for real-time monitoring and control, and evaluating the system's performance in practical use. The system integrates ESP32 microcontrollers, soil moisture sensors, a line-following robot, and a Kondular-based mobile app. Each plant is monitored by a dedicated sensor that continuously measures soil moisture levels. When a sensor detects that moisture has fallen below a user-defined threshold, configured through the app, the ESP32 triggers the robot to travel along a black line to the target plant, dispense water through a servo-controlled mechanism, and return to its base. The developed mobile app provides live monitoring, customizable thresholds for each plant, and real-time data exchange through Firebase. Sensor readings are also logged in Google Sheets for analysis and performance tracking. The system is designed for autonomous operation, independent of minimal user intervention. This system offers a smart and scalable solution for efficient home gardening and small-scale agriculture.*

Keywords: *Automated Irrigation System, Black Line Robot, ESP32, Soil Moisture*

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I. Introduction

The integration of IoT technology into gardening has introduced a more efficient and sustainable approach to water management. One notable innovation is the IoT-Based Autonomous Irrigation System, which optimizes watering schedules based on real-time soil moisture data. Traditional watering methods in home and urban gardening often result in overwatering, inconsistent timing, and unnecessary water loss, which can harm plant health and deplete resources. In contrast, smart irrigation systems equipped with soil moisture sensors continuously monitor moisture levels, ensuring water is delivered only when necessary [1]. This specific approach not only optimizes water usage but also supports water conservation, thereby making it an eco-friendly alternative to conventional practices [2]. As the plants receive ample water without the risk of overwatering, their growth and resilience improve, resulting in healthier ecosystems and more efficient agricultural systems [3].

Intelligent irrigation system integration has several advantages in both landscape and agricultural usage. The use of soil moisture sensors within the root zone provides accurate information on water demand for the automated adjustment of irrigation schedules [4]. This adaptability is valuable in situations where soil types, weather conditions, and crop requirements change. Studies have established that these systems can conserve 20-70% of water use and enhance their capacity to manage water and mitigate the impact of water scarcity [5]. Apart from water conservation, the systems protect fertile soils by preventing waterlogging and nutrient leaching, promoting sustainable agriculture.

Beyond soil moisture monitoring, smart technologies such as automated irrigation systems and real-time water quality monitoring are gaining popularity. These tools enable farmers to optimize resource use and boost productivity. With growing food demand and an increasing number of people engaging in agriculture, the adoption of smart farming solutions has increased, offering time savings, improved crop quality, and higher yields. Today, farmers can choose from a variety of technologies tailored to their farm size, crop type, and budget. While choosing the wrong solution can be costly, informed choices often lead to significant benefits [6].

A notable example of this progress is the autonomous water quality monitoring system, which eliminates the delays and high costs associated with traditional laboratory testing by providing real-time data through sensors. These systems measure key indicators such as pH, temperature, and chlorine levels using electrochemical sensors and wirelessly transmit the results to a user interface for instant analysis. This is particularly valuable in farming, environmental management, and public health, especially in remote or underserved areas where access to laboratory facilities is limited [7].

Water quality monitoring is crucial to ensure that the water used for drinking, irrigation, and industrial purposes is clean and safe [8]. Measurements like pH help detect acidity levels, temperature affects both chemical reactions and biological activity, and chlorine levels reflect how well the water has been disinfected. Automated systems can detect problems early, reducing the need for manual sampling and testing [9].

One standout innovation in this space is the Multi-Parameter Water Quality Monitoring System (MWQMS). It is designed to be low-cost, easy to use, and capable of delivering real-time data [10]. Using compact electronics and affordable sensors, it tracks key factors like pH, free chlorine, temperature, dissolved oxygen, turbidity, and pollutants like BPA [11]. It even connects to smartphones, making it ideal for low-resource areas and a fast response to any water quality issues [12]. This type of technology plays a crucial role in preventing pollution, protecting the ecosystem, and meeting environmental standards, thereby supporting sustainable water management in various settings [13].

Driving many of these smart technologies is the Internet of Things (IoT), which has become central to modern, tech-enabled farming. IoT devices such as soil moisture sensors, weather trackers, and livestock monitors help farmers collect and analyze real-time data, leading to smarter decisions about watering, fertilizing, and pest control. For example, smart irrigation systems can avoid water waste by adjusting schedules based on actual soil moisture levels [14].

That said, some challenges remain. The upfront cost of IoT systems can be high, rural areas often have limited internet access, and effective data management tools are still in the process of evolving. Even so, the IoT continues to offer exciting possibilities for enhancing efficiency, reducing waste, and encouraging sustainable, resilient farming practices [15].

II. Problem Statement

Efficient water management in plant production has long been a persistent challenge, particularly in home gardening and small-scale production units where inputs of material and room for automation are minimal. Traditional manual watering methods are often imprecise and labor-intensive, frequently resulting in overwatering or underwatering. Insufficient water weakens plants and slows their growth, while excessive watering can lead to root damage and disease. Both extremes compromise plant health and productivity. Moreover, inefficient watering practices contribute to water wastage, a growing concern in regions facing water scarcity. Without real-time info, they often must guess or follow a fixed watering schedule that does not really suit the plants.

Conventional automated systems are expensive, complex, and not easy to scale down to small-scale or domestic applications. This requires inexpensive, user-friendly products that can regulate watering operations in a smart way without continuous human intervention. To address these limitations, there is a need for inexpensive and smart irrigation systems with real-time soil moisture measurement and automatic control. This project proposes an IoT-enabled solution using ESP32 microcontrollers, soil moisture sensors, and a line-following robot. Users may remotely monitor and manage thresholds with a customized mobile application.

To enhance the capability of an autonomous plant-watering robot in managing irrigation tasks, the system should be intelligent, efficient, cost-effective, and user-friendly. To achieve this aim, the objectives of this project are as follows:

1)To design an IoT system for automated watering that enhances water efficiency in watering plants.

2)To develop a smart irrigation system by implementing mobile applications for real-time monitoring.

3)To evaluate the robotic system's performance and reliability during site testing within a small-scale gardening environment.

III. Methodology

This project creates an automated watering system for two plants using a Kodular app, an ESP32-based line follower robot, and soil moisture sensors. A sensor is used to continuously read the moisture content of the soil for each plant. The system instructs the robot to follow a black line path to the plant that needs water when its moisture content drops below a user-defined level. A servo motor regulates the watering procedure when it arrives, and the robot returns to its starting place after it is finished. With the Kodular app, customers can manually stop watering, when necessary, establish desired moisture levels, and view sensor data in real time. The technology offers a simple and effective watering solution that operates entirely autonomously without the need for alerts.

A. Block Diagram

Fig. 1 illustrates the layout of an automated plant waterer based on two ESP32 microcontrollers, connected via Wi-Fi, and utilizes Google Sheets and Firebase. The first ESP32 performs plant monitoring by sensing the real-time soil moisture content from a sensor; if the soil moisture content falls below a set level, it turns on a water pump via a relay to supply water to the plant. The second ESP32 controls a robot with differential IR sensors, translation servo motors and nozzle motors, and a battery that can travel along a black line to water plants precisely. All sensor data and control commands are sent to Firebase, which serves as an intermediary of real-time communication between the two ESP32 boards and a mobile app. The system allows users to monitor moisture levels, determine alert levels, and remotely control the system, with sensor readings logged to Google Sheets for analysis. The integration provides efficient, automated, and remote-controllable plant care.

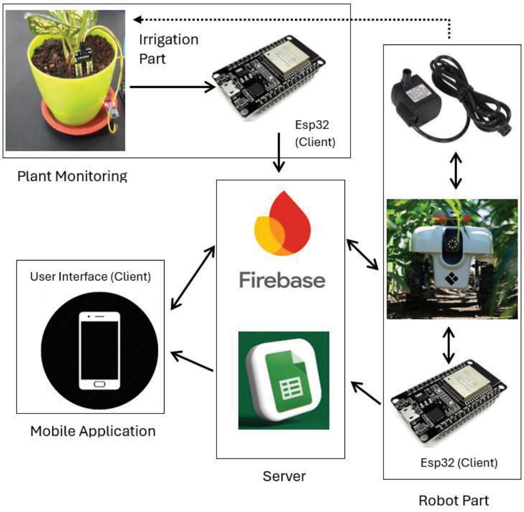
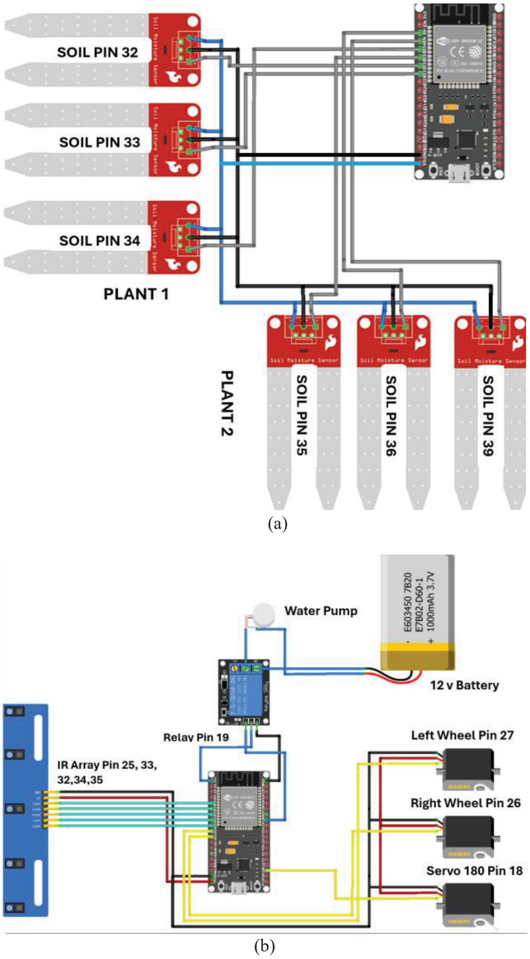


Fig. 1. Project Block Diagram

B. Schematic Diagram

The schematic diagram in Fig. 2 illustrates the design of the smart watering system, combining plant monitoring and autonomous robotic action. An ESP32 microcontroller is a central hub for receiving input from six soil moisture sensors (three sensors for each plant) to enable precise, multi-point moisture measurement for each plant. These sensors are left permanently plugged into the ESP32 to allow real-time, continuous data readings for accurate watering decisions. An IR sensor is used to navigate the robot black line. Navigation is completed by two servos that move the left and right wheels, and irrigation is accomplished using a 12V-powered water pump driven by a relay. Dispensing water is also controlled by 180 servos, giving precise watering. This fully integrated system provides autonomous travel, location detection, and smart watering in response to sensor input.



(a)

(b)

Fig. 2. Schematic connections. (a) Irrigation Part (above), (b) Robot Part (below)

C. Flowchart of the System

The system flowchart is illustrated in Fig. 3. It begins by powering on and booting the ESP32 microcontrollers used in the robot and irrigation systems, establishing communication protocols, reading sensors, and controlling motors. It continuously reads the soil moisture levels from sensors placed at different plant zones, stores this information in Google Sheets for historical data, and pushes real-time readings to a mobile app, as well as user-specified moisture thresholds. The system compares the current moisture levels to the set level; if the soil is sufficiently moist, it continues to monitor. If the level is less than the standard, real-time measurements are sent to Firebase, which initiates the robot autonomous driving to the target plant through line-following. When it is at the location, the robot employs a servo to water the soil as it continues to monitor moisture levels. Once the target level is reached, the robot documents the event and proceeds to the next plant to be irrigated or returns to the starting position if it has no other plants to irrigate. The process is a loop with a good cycle between ESP32, Google Sheets, Firebase, and the mobile application. This may cause the watering process to synchronize with the objective, which is efficient and adaptive as it waters only when necessary, reducing water waste.

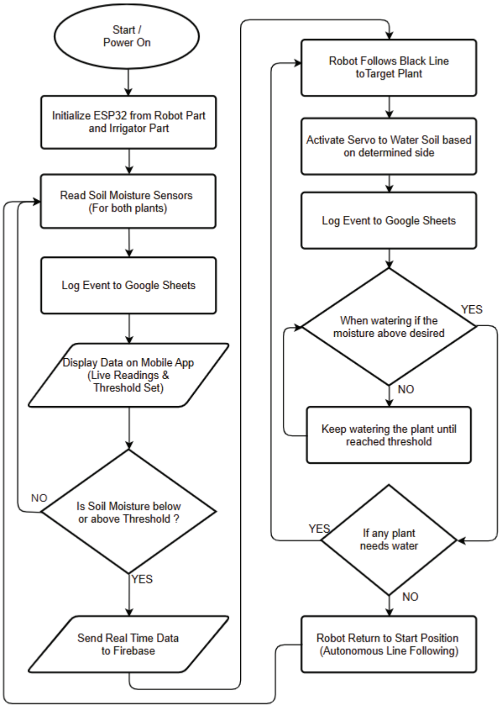
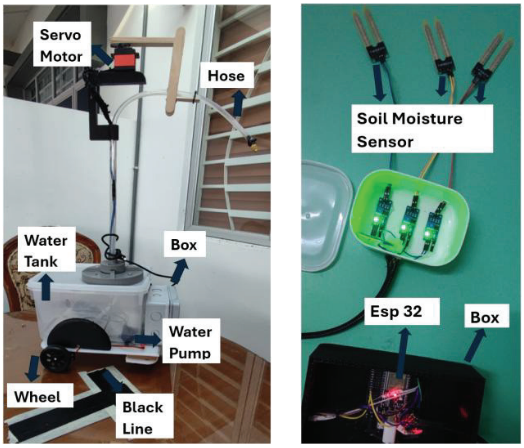


Fig. 3. Flowchart of the System

IV. Hardware Design

The automated robotic irrigation system as shown in Fig. 4(a) works as a demonstration of integrated mechanical systems and IoT-based smart agriculture. It consists of a mobile platform with a water tank guided along the path marked by a black line, thus exemplifying autonomous navigation. The contained water pump and servo motor enable controlled irrigation, demonstrating a practical application of fluid mechanics. Of course, soil moisture sensing is demonstrated using three sensors, each in communication with a single plant to provide real-time data. Fig. 4(b) shows they reside within waterproof cases, ensuring the reliability of the sensor in a real-world setup. The measured data are analyzed with an ESP32 microcontroller, making a case for an embedded system application. The system is housed in a protective enclosure, with LEDs indicating system status. The project serves as a classic example of real-time data acquisition, interaction, and automation applied to agricultural education.



(a) (b)

Fig. 4. Assembled Hardware. (a) Robot Part (left), (b) Irrigation Part (right)

V. Results and Discussion

This section presents experimental methodology and findings, emphasizing the robotic system's performance, sensor accuracy, and watering efficiency. The proposed IoT-enabled robotic watering system offers distinct advantages over existing smart irrigation solutions in terms of efficiency, scalability, and cost. Unlike conventional systems that rely on fixed infrastructure such as drip networks or automated sprinklers, this design employs a mobile robotic platform that autonomously navigates plant locations and dispenses water only when necessary. This targeted approach reduces wastage, improves distribution precision, and provides greater flexibility to adapt to changing plant arrangements without requiring costly modifications to irrigation layouts.

A. Experiment Site Visit

The robot watering system was also successfully tested in a small garden plant nursery to gauge its real performance and usability as shown in Fig. 5. Its installation included a wheeled robot prototype, base unit, elevated watering mechanism, nozzle, hose, and wood parts, indicating its initial state of development. Placed on a black 'T'-shaped course set on concrete, the robot traversed a route to plant sections along a mapped path, responding to sensor readings in soil moisture set close to selected pots. A suitable location was chosen, offering reduced sunlight and facilitating easy observation. The trial, observed by nursery staff among lush plants, provided a good response to system operation, environmental stability, and performance in real world in agriculture.

Fig. 5. Project Experiment Site Visit

B. Efficiency Water Usage

The primary goal of this project is to create a system that is not only more efficient but also less wasteful than existing systems already in place, especially in comparison to hand-watering plants. To measure the system's performance, this project conducted experiments and collected data. Not overfeeding plants with too much or too little water is a big consideration. If the technology functions well, it will demonstrate that it can effectively address the issues of underwatering and overwatering plants.

Table I presents the water usage data for the robot system, while Table II displays the water usage data for manual watering. These data have been collected, and a comparison of water usage between the robotic system and the manual system is presented. The robot system produced a total of 665 ml (0.665 Liters) of water in three days. This water use was optimized for various watering times and altered pump durations, such as 3 seconds on Day 1 (285 ml) and 4 seconds on Day 3 (380 ml); however, no watering was conducted on Day 2. Meanwhile, the manual water method had a consistent water use of 250 ml per day, amounting to 750 ml (0.750 Liters) over the same time.

TABLE I
WATER USAGE BY THE ROBOT SYSTEM

Test Day	Watering Time	Pump ON Duration (sec)	Total Water Dispensed (ml)
Day 1	9.00 AM	3	3 sec x 95 ml/sec = 285 ml
Day 2	No Watering	0	0 ml
Day 3	2.00 PM	4	4 sec x 95 ml/sec = 380 ml
Total Robot Water in (3 Days)	-	**7**	**665 ml (0.665 Litres)**

TABLE 2
WATER USAGE BY THE MANUAL WATERING

Test Day	Watering Time	Total Water Dispensed (ml)
Day 1	9.00 AM	250
Day 2	9.00 AM	250
Day 3	9.00 AM	250
Total Manual Water in (3 Days)	-	**750 ml (0.750 Litres)**

According to the three-day statistics, the robotic system used only 665 ml of water, compared to 750 ml when manually watering. This represents a water saving of 11.33%. This is a clear sign that not only is the robotic system water-saving, but it is also able to prevent overwatering and underwatering effectively. Therefore, the system successfully fulfills its primary objective of providing an effective, water-saving irrigation system that accurately responds to the plant's real soil moisture needs. This analysis reveals that the robotic system has strong potential for enhancing the efficiency of water usage and nutrient uptake, but further studies with actual experimental data are highly recommended for complete validation.

C. Apps Development

This is the user interface, as shown in Fig. 6, of the application for monitoring and managing the smart watering system. Both 'PLANT 1' and 'PLANT 2' have three soil moisture sensors placed at different depths, which are at the top, middle, and bottom of the plant to lead to better soil conditions. The blue slider can be used to enter the target moisture level for a specific plant, which can be adjusted to suit various plant types with varying water needs. For instance, in the illustration shown, 'PLANT 1' has a target value of 50% moisture, and the actual value is 69%, whereas 'PLANT 2' has a target of 50%, and the actual moisture level is 91%. Once the moisture level drops below the set limit, the robot will automatically head to the plant and begin watering. This system will keep watering the plant until the sensor has achieved the average threshold that has been set by the user, so it can reduce the waste of the water in an efficient way.

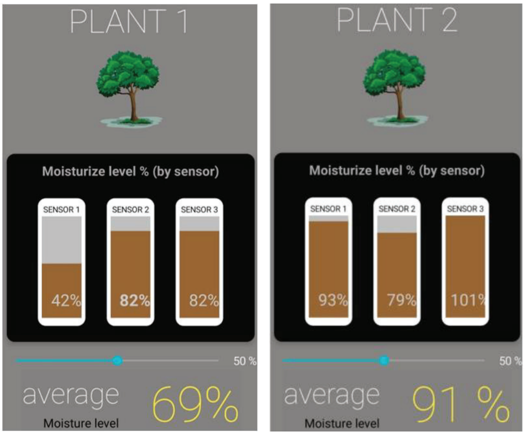
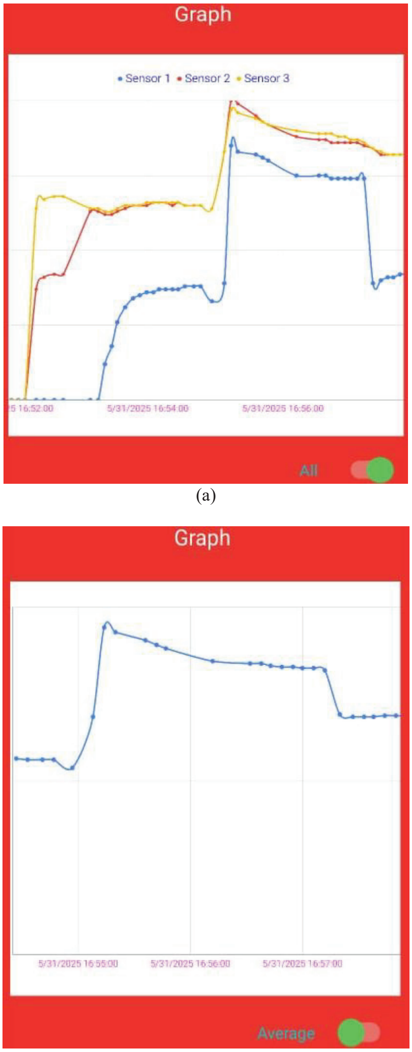


Fig. 6. Plants Reading Interface

All real-time sensor data from the ESP32 microcontrollers is continuously logged into Google Sheets for monitoring and analysis. Simultaneously, this data is transmitted to a mobile app, enabling real-time display and interaction. As illustrated in Fig. 7(a) and Fig. 7(b), the app presents two moisture graphs: one showing individual sensor readings (Sensor 1, 2, and 3) and another displaying an average trend derived from the latest 50 readings. This dual-graph interface allows users to observe both detailed and smooth moisture patterns. A toggle button in the GUI enables easy switching between these display modes.



(a)

(b)

Fig. 7. Moisture graph. (a). For the individual sensor, (b). Average trend

In the "ROBOTIC MAPPING" screen, the robot's navigation path is displayed graphically, as illustrated in Fig. 8. The main corridor and lateral branches for plant placement are always outlined with a thick black line, while the various stations are labeled 1 to 4. The starting point of the robot is labeled as "Initial". The path the robot usually takes is represented by a blue dashed line with arrows showing the direction. This path comprises stops at each junction, where plants will be watered if the "Start Watering" button is pressed. If one selects the "Stop Watering" option in the interface, the robot will not move, even if the plants require water. A shortcut icon exists, connecting to Google Sheets, where timestamped watering logs can be viewed in order to keep track of the irrigation system.

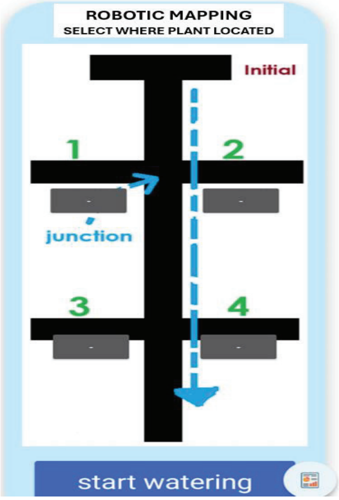
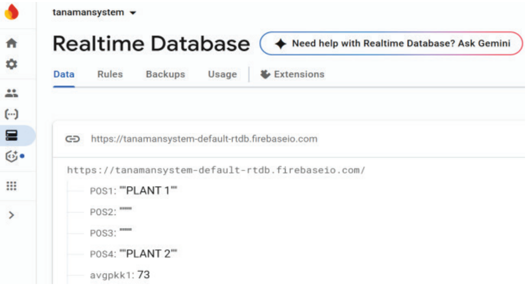


Fig. 8. Robotic Mapping of this System

D. *System Result*

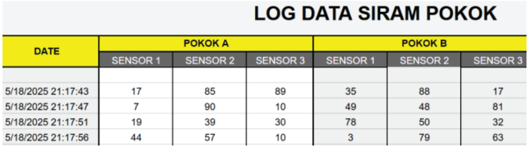
Fig. 9 shows the Firebase Realtime Database tab used in this project, named "tanaman system", with current key value pairs such as POS1: "PLANT 1," which indicates the location of the plant, and avgpkk1: 0, which represents the average water content for Plant 1. Both a real-time communications platform and a cloud database, Firebase Realtime Database stores data as a single state that is being constantly revised, each key has only the most current value, replacing the old ones. This design facilitates strongly efficient two-way synchronization, enabling connected clients such as the robot and mobile app to communicate and instantly propagate data changes. This design does make it challenging to draw historical reports or monitor previous changes unless further logic is added, such as timestamping updates or mirroring the data to an analytics-targeted database. Therefore, while the Firebase Realtime Database is sufficient for apps due to its speedy, cloud-hosted, real-time data sharing, it is not the best option for historical analysis alone.



```
https://tanamansystem-default-rtdb.firebaseio.com
https://tanamansystem-default-rtdb.firebaseio.com/
    POS1: ""PLANT 1""
    POS2: """"
    POS3: """"
    POS4: ""PLANT 2""
    avgpkk1: 73
```

Fig. 9. Firebase Interface

The "LOG DATA SIRAM POKOK" (Plant Watering Log Data) table, as shown in screenshot of table Fig. 10, is well designed for use in Google Sheets, making it easy to log and analyze sensor data over time. It systematically records readings from two plants (Pokok A and Pokok B), each equipped with three sensors, with entries organized by date and timestamp (e.g., 5/18/2025 21:17:43). This detailed logging supports the creation of graphs to track factors such as plant health, watering efficiency, and soil moisture trends in real time monitoring. By correlating sensor readings with watering records, users can further analyze soil composition and water retention, making the table a valuable resource for both horticultural and agricultural research and management.

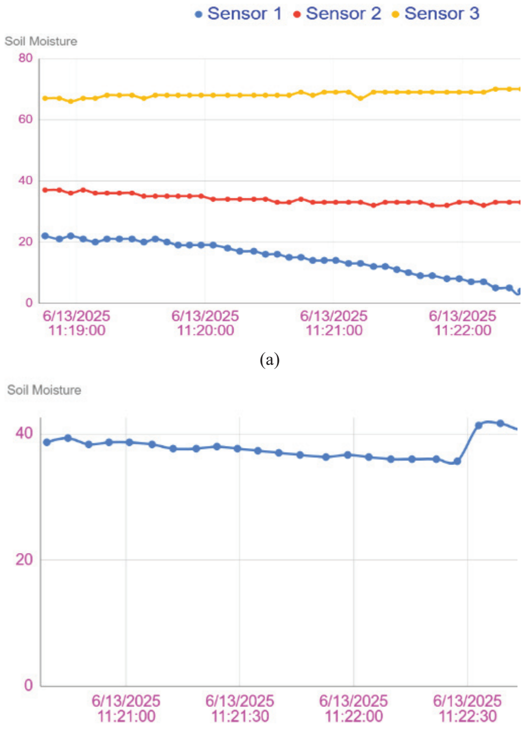


LOG DATA SIRAM POKOK

DATE	POKOK A			POKOK B		
	SENSOR 1	SENSOR 2	SENSOR 3	SENSOR 1	SENSOR 2	SENSOR 3
5/18/2025 21:17:43	17	85	89	35	88	17
5/18/2025 21:17:47	7	90	10	49	48	81
5/18/2025 21:17:51	19	39	30	78	50	32
5/18/2025 21:17:56	44	57	10	3	79	63

Fig. 10. Example Watering Plant Log Data

Fig. 11(a) and Fig. 11(b) illustrate live soil moisture readings from three sensors placed at different depths in the soil during a test under direct sunlight, validating the system operation. Sensor 1 (top layer) exhibited the fastest rate of moisture decline due to evaporation on the surface. Sensor 2 (middle layer) maintained moderate readings, and Sensor 3 (bottom layer) consistently recorded the highest level of moisture, reflecting the natural water retention capacities in deeper soils. The graph also shows a clear drop and increase in moisture, indicating the system's ability to detect drying conditions and release water. Overall, it clearly demonstrates how soil moisture varies with depth and confirms the system's responsive control under intense sunlight.

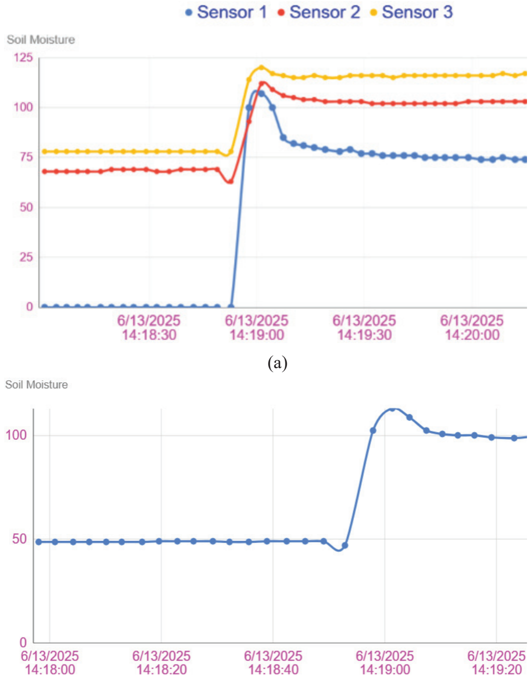


(a)

(b)

Fig. 11. (a) Graph Sensor of Soil Moisture (b) Time Taken (before)

The two graphs in Fig. 12(a) and Fig. 12(b) provide testimony to the drying out of a plant and subsequent rewatering. The above graph shows Sensor 1's moisture level at nearly zero, while Sensors 2 and 3 are moderate, reflecting the dryness of the plant after one hour of direct sunlight, leaving the levels below 40 percent. A sharp spike in all sensor readings as shown in the graph is a guarantee of active watering, which replenishes moisture levels quickly. Similarly, the graph illustrates the plant's initial stable moisture level at 50, followed by a sudden decline, and then a sharp upturn beyond 100, indicating that watering had begun after the level allegedly fell below 50. This water increase supports successful rehydration. The two graphs combined demonstrate the system's accurate detection of dryness and its automatic watering response, which maintains soil moisture within its best range.



(a)

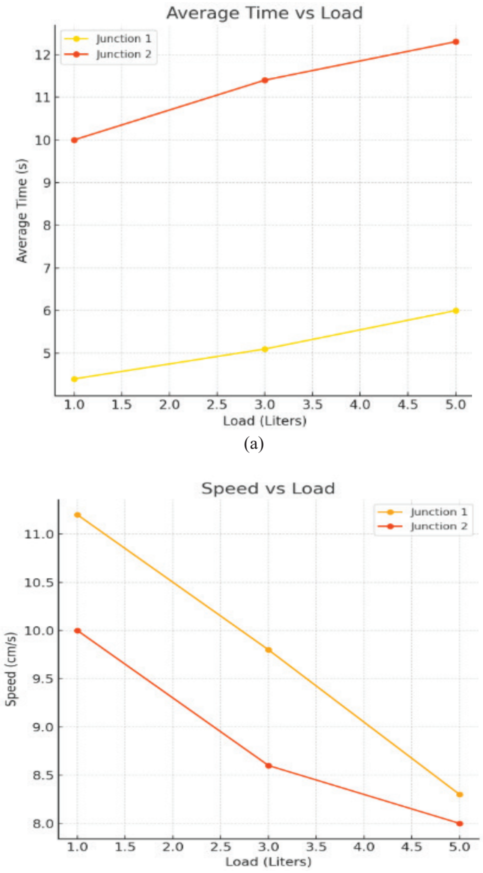
(b)

Fig. 12. (a) Graph Sensor of Soil Moisture (b) Time Taken (after)

E. Performance of Robotic

The graph, as shown in Fig. 13 (a), displays the average time (s) versus load (L), indicating a clear increase for both Junction 1 and Junction 2, which corroborates the observation that as the load on the robot rises, the average time spent traveling to each junction also increases. The lines on the graph trend upwards, representing a curve with an almost linear trend, especially at heavy loads, indicating that the slope of time with weight intensifies at greater weights. This graphical presentation validates data-derived findings and highlights the impact of load on the robot's travel performance. The graph illustrates how the performance of loads is influenced by them and argues that future improvements in weight control or motor control are necessary to maintain efficiency. This results in the robot's weight and average speed being inversely related, meaning that the robot's travel efficiency is affected if heavier loads are not reduced.

The average speed versus load as shown in Fig. 13(b) says that robots decelerate with increasing load. The robot moves at a high speed when transporting 1 litre of water, but its speed decreases when the load is increased to 3 litres and 5 litres. This can be observed at Junction 1 (50 cm) as well as Junction 2 (100 cm). At Junction 1, the speed decreases from 11.24 cm/s (with 1L) to 8.25 cm/s (with 5L). At Junction 2, the speed decreases as well, from 10.03 cm/s to 8.07 cm/s. This means that the robot spends more time with heavier weights in reaching the plant, as more effort is required. Due to its shorter distance, the robot is slightly quicker in reaching Junction 1. Summarizing, the graph indicates that the robot moves more slowly when it needs to carry a greater load. This is relevant to the amount of water the robot can carry in a smart watering system.



(a)

(b)

Fig. 13. (a) Graph Average Time vs Load. (b) Graph Speed vs Load

VI. Conclusion

This project contributes a proof-of-concept prototype that demonstrates water savings by developing an automated and intelligent watering system which enhances both efficiency and usability. Through the integration of IoT technology and soil moisture sensors, the system optimizes water usage, reduces wastage, and ensures plants receive the right amount of water. The mobile application further enhances usability with real-time monitoring and remote control, while the robotic platform reliably navigates its path, identifies plant locations, and dispenses water accurately. These outcomes highlight the practical value of an IoT-enabled robotic watering system in promoting water conservation, supporting plant health, and reducing manual effort in gardening or nursery environments.

For future improvements, the system can be enhanced with obstacle avoidance sensors such as ultrasonic or LiDAR to improve safety and navigation in dynamic environments. Moving beyond fixed black-line guidance toward AI or vision-based plant detection would make the robot more flexible and autonomous. Additionally, integrating environmental sensors such as temperature, humidity, and light intensity would provide a more complete picture of plant conditions. With the support of data analytics, these inputs could generate smarter and more adaptive watering schedules, further improving reliability, scalability, and practical use in precision agriculture.

Lastly, due to the limited scope of trials in this study, future work will expand experimental validation across a wider range of plant species, prolonged monitoring periods, and diverse environmental conditions. This will enable a more rigorous assessment of system performance under real-world variability. Statistical analyses and reliability metrics, e.g. water savings and sensor accuracy, will be incorporated to quantify benefits and support reproducibility. Identified limitations e.g. internet dependency, battery life, maintenance overhead, and scalability across larger deployments will be systematically addressed. Furthermore, future iterations will provide deeper technical insights into the mobile application, including communication protocols, latency benchmarks, and error-handling mechanisms to ensure seamless user experience and operational resilience.

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Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Muhammad Hamsyari Hamizan Muhammad Zaidi, Kim Seng Chia; data collection: Muhammad Hamsyari Hamizan Muhammad Zaidi; analysis and interpretation of results: Muhammad Hamsyari Hamizan Muhammad Zaidi, Kim Seng Chia; draft manuscript preparation: Muhammad Hamsyari Hamizan Muhammad Zaidi, Kim Seng Chia; Manuscript editing and revision: King Lee Chua, Xien Yin Yap. All authors reviewed the results and approved the final version of the manuscript.

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