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Performance of an internet of things based plant monitoring and irrigation system using solar energy

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ABSTRACT

This paper aims to present an internet of things (IoT) based plant monitoring and irrigation system powered by solar energy. The system enhances plant care by continuously monitoring environmental conditions such as soil moisture, temperature and humidity with real data displaye via the Blynk platform. User can remotely monitor and control irrigation through interactive widgets, ensuring efficient plant management. By integrating solar energy, the system operates sustainably, and reduce reliance on conventional electricity. Performance evaluation demonstrates a temperature sensor accuracy of 98%, a humidity sensor accuracy of 95% and soil moisture sensor error margin of 2-3%. Experiment results indicate improved plant growth of 7-8% compared to traditional farming practices, showcasing the system's potential for increased productivity and conversion. This research highlight the benefits of combining IoT and renewable energy to offer an innovative, and eco-friendly solution for agricultural management.

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1. INTRODUCTION

In recent years, the internet of things (IoT) has significantly transformed agriculture, offering modern solutions to traditional challenges. Agriculture, which traditionally depended on manual labour and subjective judgement, is undergoing a rapid technological shift towards automation and data driven decision making. One of the critical problems in conventional agriculture is the inefficiency in resource management, especially water and energy usage in irrigation. Excessive or insufficient watering often leads to poor crop yield, while reliance on conventional power sources increases operational costs and environmental impact.

Several studies have contributed to IoT application in agriculture. For instance, [1]-[4] have demonstrated how IoT systems can collect real time data to enhance farming operation, focusing on irrigation and environmental monitoring. Traditionally, agriculture heavily relied on manual labor and guesswork, making it challenging to achieve optimal plant growth and maximize crop yield. Farmers had to manually monitor environmental conditions, such as soil moisture, temperature, humidity, and light levels [5]. This lack of real-time data often resulted in over-watering or under-watering, inadequate nutrient supply, and inefficient resource utilization. However, with the advent of IoT, farmers now have access to advanced plant monitoring and irrigation systems that utilize interconnected devices to gather data and provide actionable insights. By deploying various sensors and actuators throughout the farm, these IoT systems can collect and transmit valuable information in real-time [6]-[8].

Solar-powered IoT systems offer increased autonomy and resilience, as they can operate even in remote or off-grid areas. Previous study explored, the energy captured by photovoltaic (PV) panels can be stored in batteries, ensuring a continuous power supply for the IoT devices and maintaining data collection and transmission even during cloudy days or power outages [9], [10]. In addition to optimizing irrigation, IoT-based systems in agriculture can provide valuable insights for precision farming [11]-[13]. By analyzing data from various sensors, farmers can identify patterns, detect anomalies, and make data-driven decisions to improve crop yield, quality, and disease management.

For instance, the data collected by IoT devices can help identify early signs of plant stress, nutrient deficiencies, or pest infestations, enabling timely intervention and reducing crop losses [14]-[17]. Moreover, the integration of IoT into agriculture facilitates remote monitoring and control. Farmers can access real-time data and control the irrigation system or adjust environmental parameters from anywhere, using their smartphones or other connected devices. This level of flexibility and accessibility empowers farmers to make informed decisions promptly, optimizing resource allocation and mitigating risks [18]-[20].

This study aims to fill these gaps by developing an IoT-based plant monitoring and irrigation system powered by solar energy. The key novelty of this work lies in the integration of solar energy as a sustainable power source, ensuring the system's operability in remote or off-grid areas. Additionally, the system features real-time monitoring and control, using sensors to manage water levels based on soil moisture, temperature, and humidity data. Unlike previous works, this system not only monitors but also autonomously controls the irrigation process, optimizing water usage and enhancing plant growth.

The following sections of this paper detail the system's design, implementation, and testing. Section 2 describes the hardware and software architecture, focusing on sensor integration and solar power management. Section 3 presents experimental results, including sensor accuracy and system performance under various environmental conditions. Finally, section 4 discusses the impact of the system on water conservation and plant health, demonstrating its relevance in sustainable agriculture. With the continuous advancements in IoT technologies, the future of agriculture holds tremendous potential for increased efficiency, reduced resource wastage, and improved global food security [21]-[23].

2. METHOD

This section provides the implementation of the IoT-based plant monitoring and irrigation system, powered by solar energy. The methodology is outlined in a step-by-step manner to ensure reproducibility, with justifications for the selected approaches based on theoretical and practical considerations. The system integrates multiple sensors for environmental monitoring, actuators for irrigation control, and a solar-powered energy supply, all managed through an IoT framework.

The system's architecture is depicted in Figure 1, which illustrates the interconnections between sensors, the microcontroller, and the water pump. The microcontroller receives sensor inputs, processes the data, and initiates the irrigation process based on pre-set thresholds. A PV panel is utilized as the primary power source for the system, charging a power bank that supplies energy to the NodeMCU ESP32 microcontroller, sensors, and actuators. In instances of insufficient solar irradiance, such as during extended periods of cloud cover, a wall charger is connected to maintain system functionality.

During the rainy season, a wall plug charger will be used to charge the power bank. Then soil moisture sensor will be installed on the plant tray and will be used to detect soil moisture. The ultrasonic sensor will then be inserted in the top of water tank in order to monitor the water level. After controller receive input from ultrasonic and soil moisture level sensor, it will control the water pump to make the water tank to supply water to the system. The DHT22 sensor will be installed on the plant tray in order measure temperature and humidty of plant surrounding [24], [25]. All the process will be conduct according to coding preset. After the process is done, data will be collected. Users can see all the data collected by using the Blynk app via mobile phone. Figure 2 show overall project prototype.

The Blynk platform is used to allow users to monitor real-time data and control the irrigation system remotely. Data from the soil moisture, temperature, and humidity sensors, as well as water levels, are sent to the Blynk cloud, where they are visualized on a mobile app. Users receive notifications for critical events, such as low water levels, and can manually trigger or adjust the irrigation system as needed.

The experimental setup included two plant trays, Tray A used the IoT-based irrigation system and Tray B utilized a traditional manual irrigation method for comparison. Both trays were placed in identical environmental conditions, and spinach was selected as the test plant species due to its well-documented water requirements. Over a 7-day observation period, data were collected on water consumption, plant growth, and sensor performance. The system was also tested under various weather conditions, including sunny and cloudy days, to assess the effectiveness of the solar power system.

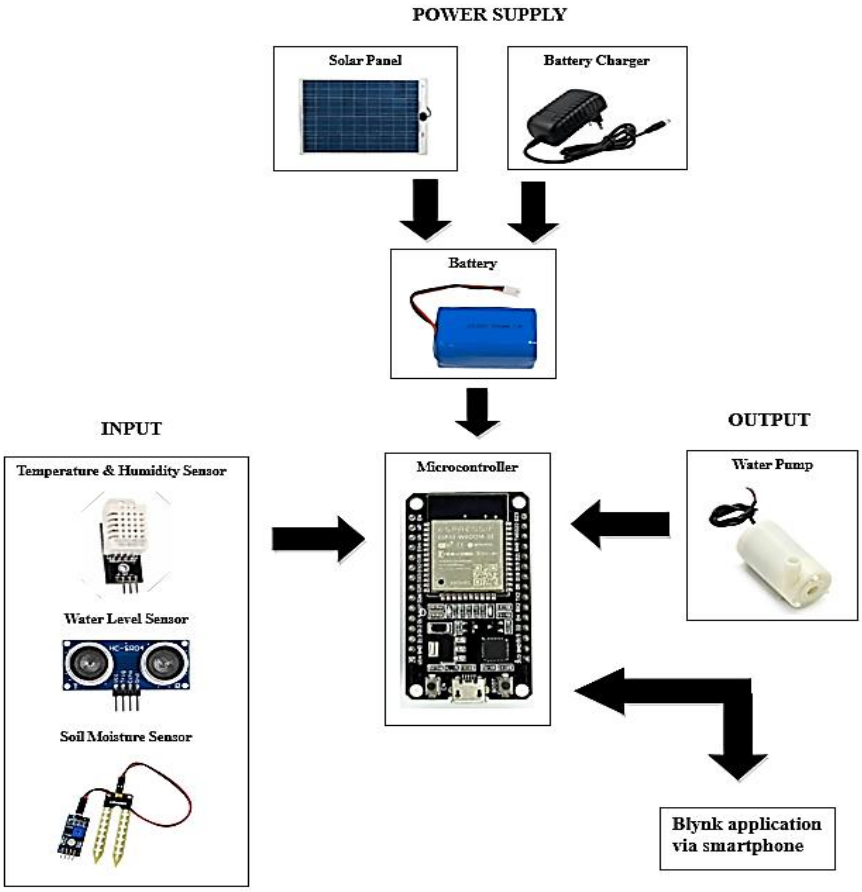

Figure 1. IoT system block diagram

Figure 2. Overall hardware system

3. RESULTS AND DISCUSSION

The findings of this research demonstrate the feasibility and effectiveness of an IoT-based plant monitoring and irrigation system powered by solar energy. The system's ability to operate autonomously in remote areas without a consistent electricity supply represents a significant advancement in precision agriculture, particularly in regions where traditional grid electricity is unavailable. The results indicate that the solar-powered IoT system can not only maintain continuous operation but also optimize resource usage, including water and energy.

3.1. Battery based solar charging system

On this part, three data samples were collected from 9 AM to 5 PM to show the difference in voltage and current for one day. As a result, the voltage and current readings are shown in recorded tables and plotted graphs. According to Table 1, the current reading is exceptionally low, attributed to the presence of clouds and drizzle persisting from morning until evening. Figure 3 illustrates that the maximum power for the day occurs at a current value of 0.48 A. Although it is still capable of charging the battery storage, as the voltage has reached 4 V, the charging process is notably sluggish.

Table 1. Reading voltage and current for sample 1

Times (Hours)	Voltage (V)	Current (A)
9 AM	4.12	0.16
10 AM	4.11	0.14
11 AM	4.13	0.16
12 PM	4.16	0.20
1 PM	4.19	0.48
2 PM	4.18	0.43
3 PM	4.17	0.36
4 PM	4.10	0.13
5 PM	4.09	0.11

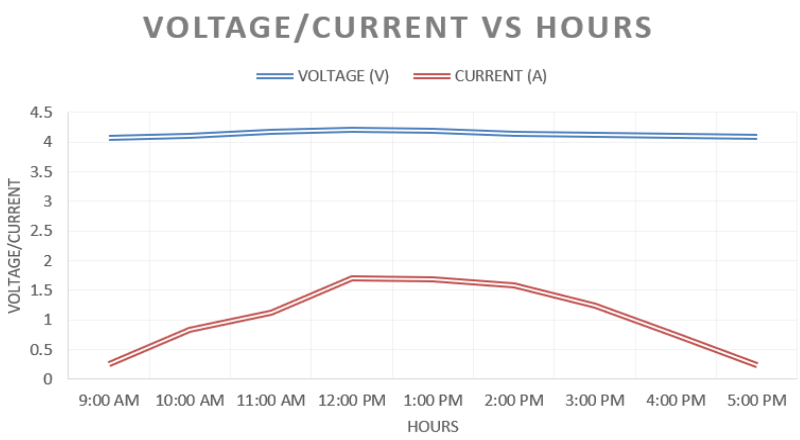

Figure 3. Graph of reading voltage and current for sample 1

According to Table 2, the voltage reading remains stable from morning until evening. Figure 4 illustrates that the maximum power for the day occurs at a current value of 1.26 A at 1:00 PM. As depicted in Figure 4, at 3:00 PM, the current drastically drops due to the onset of rainy weather. In sample two, it is evident that the battery storage can be charged more rapidly because the current reading is high from 11:00 AM to 2:00 PM.

According to Table 3, the voltage reading remains stable from morning until evening. Figure 5 illustrates that the maximum power for the day occurs at a current value of 1.71 A at 12:00 PM. As depicted in Figure 5, it can be observed that the current on that day is very high due to sunny weather from morning until evening. In sample three, it is evident that the battery storage can be charged more rapidly because the current reading is high almost all day.

Table 2. Reading voltage and current for sample 2

Time (Hours)	Voltage (V)	Current (A)
9 AM	4.09	0.44
10 AM	4.15	0.61
11 AM	4.20	0.86
12 PM	4.21	1.10
1 PM	4.22	1.26
2 PM	4.19	1.09
3 PM	4.13	0.24
4 PM	4.10	0.19
5 PM	4.09	0.16

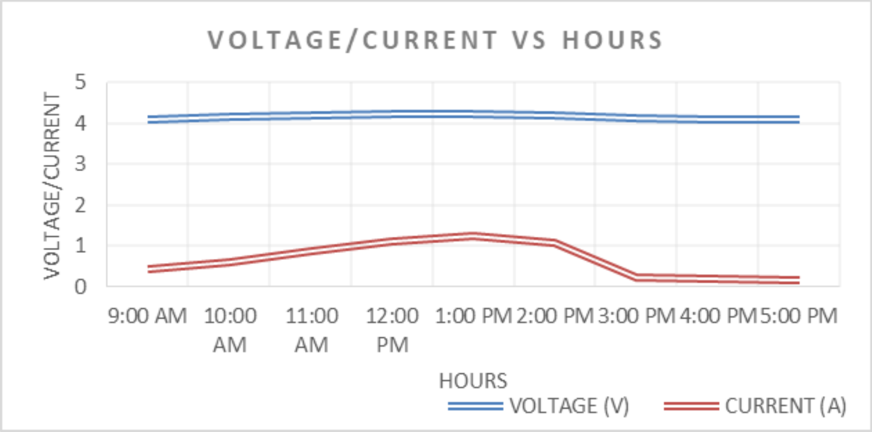

Figure 4. Graph of reading voltage and current for sample 2

Table 3. Reading voltage and current for sample 3

Times (Hours)	Voltage (V)	Current (A)
9 AM	4.08	0.26
10 AM	4.10	0.83
11 AM	4.18	1.12
12 PM	4.20	1.71
1 PM	4.19	1.68
2 PM	4.14	1.59
3 PM	4.13	1.24
4 PM	4.10	0.74
5 PM	4.09	0.24

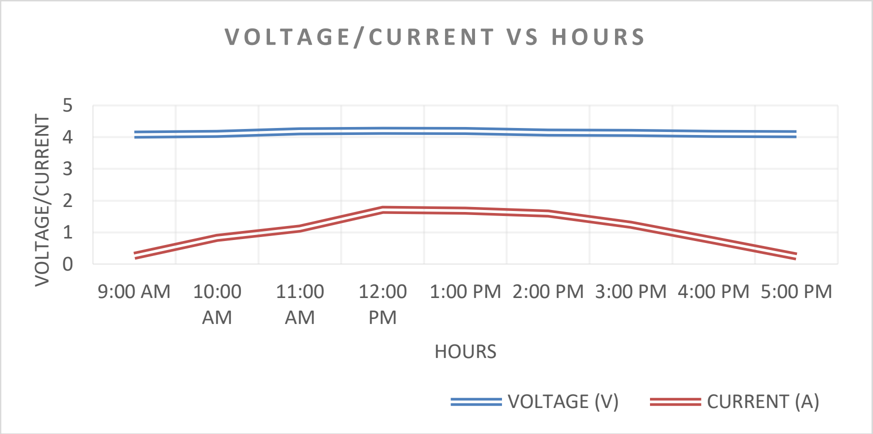

Figure 5. Graph of reading voltage and current for sample 3

Based on the result of three samples, it can be concluded that the solar system set up for the project is capable of charging the power bank. However, the charging speed is dependent on the weather conditions on the days. The more sunlight there is, the higher the speed at which the solar system can charge the power bank.

3.2. Data of temperature and humidity sensor by comparing data value with weather forecast

In this experiment, the sensor are placed at the same location and time from 9 AM to 9 PM to measured the temperature and humidity. In Figure 6, the DHT22 sensor was positioned on the side of the plant tray to monitor the temperature and humidity of the surroundings. Figure 7 show data are taken from Durian Tunggal to see the range of the result in span of 12 hours.

Figure 6. Temperature and humidity sensor on plant crop

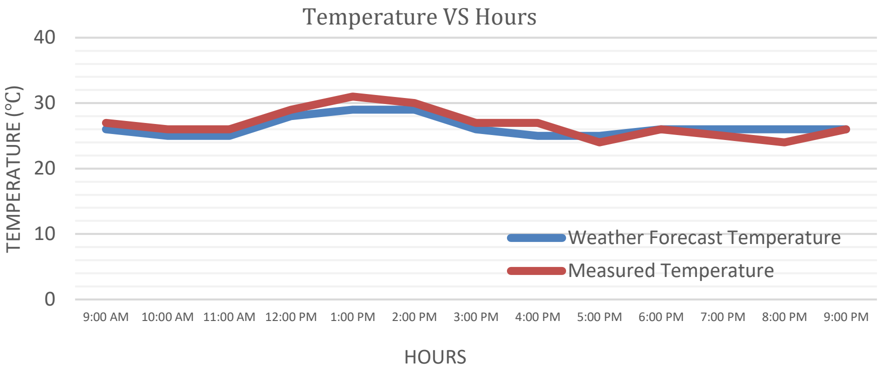

Figure 7. Temperature comparison chart

Environment temperature value is an additional data that has been add to this system to monitor the optimum environment's temperature to the plants. Ideal temperature for most plant is in between 23-35 °C including the plant that has been tested with the system which is spinach. Based on Figure 8, it can be seen that there is not much difference in the values, as the data is plotted almost at the same point for temperature. Due to a ±2% error accuracy, as stated in the sensor datasheet, resulting in small differences between the data taken, the sensors can be deemed as accurate.

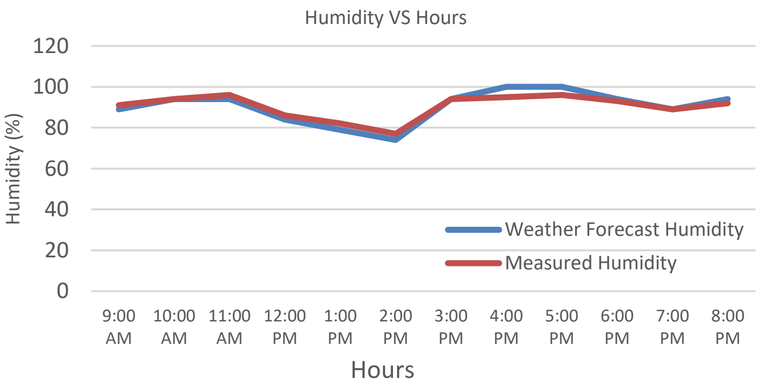

Figure 8. Humidity data comparison chart

Humidity value is an additional data that has been add to this system to monitor the optimum environment's humidity of the plants. The best humidity value for most plants is around 60%-80% including the plant that has been tested with the system which is spinach. There is not much difference in the values, as the data is plotted almost at the same point for humidity. Due to a ±2-5% error accuracy, as stated in the sensor datasheet, resulting in small differences between the data taken, the sensors can be deemed as accurate.

3.3. Data of soil moisture sensor

In this section, data were collected every hour throughout the week of observation while the system operated daily. During the two days of observation, the weather remained hot. As shown in Figure 9, the soil moisture sensor is embedded in the plant crop to obtain soil moisture values for the crop. As depicted in Figures 10 and 11, the collected data from the graphs varies between each day. This discrepancy is attributed to the influence of surrounding conditions, particularly in terms of temperature and humidity.

Figure 9. Plant crop with soil moisture sensor

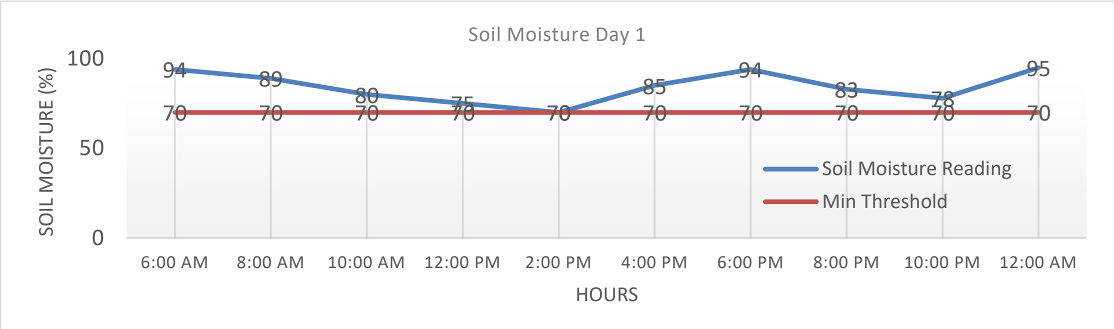

Figure 10. Soil moisture data day 1

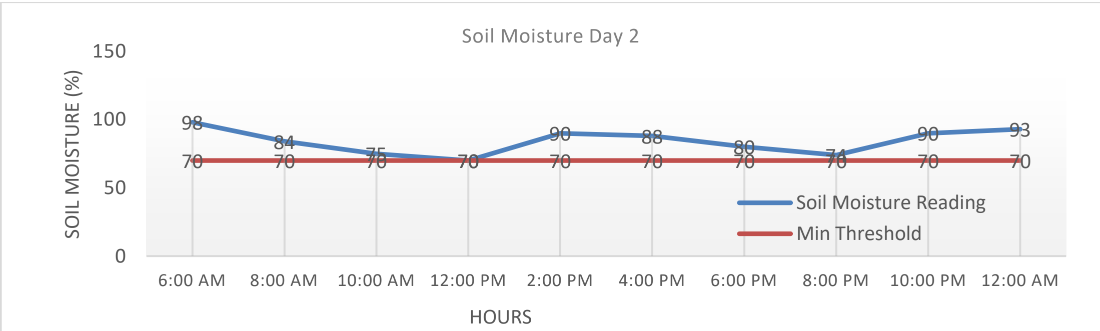

Figure 11. Soil moisture data day 2

The soil moisture sensor is employed to obtain readings of the soil moisture level. The optimal condition for plant survival dictates that the soil should not be excessively wet or waterlogged. Consequently, the system has been configured to send an alert warning to the user to irrigate the soil only when the moisture level falls below 70, considering that the moisture level readings range from 0 to 100. It can be concluded that this system is effective, as indicated by the graph. The moisture level never drops below the minimum threshold for soil moisture since irrigation commences when the soil moisture level decreases below 70.

3.4. Data water consumption

In this section, all the data recorded for water consumption used in the irrigation process is documented in Table 4. The experimental setup involved two plant trays: based on Figure 12 show, Plant

Tray A, which utilized an IoT plant monitoring and irrigation system, and based on Figure 13 show, Plant Tray B, which employed a traditional irrigation system. Data collection was scheduled daily at 12 PM over a span of 7 days. Both plant trays had identical measurements for the plant tray and water tank (width: 14 cm, height: 26 cm, and length: 21 cm).

Table 4. Water comsumption for the irragation process

Days	Plant Tray A (Liter)	Plant Tray B (Liter)
1	6.5	7.3
2	5.0	7.3
3	4.7	7.3
5	5.3	7.3
6	5.5	7.3
7	4.4	7.3
Total water used	31.4	51.1

Figure 12. Plant Tray A (IoT system)

Figure 13. Plant Tray B (traditional manual)

For Plant Tray B, the traditional irrigation system involves applying a fixed amount of water, approximately 7.3 liters per day, during the irrigation process. Plant Tray A used the data collected from the ultrasonic sensor to measure the water consumed for the irrigation process via the IoT of the system. For calculating the water consumed in Plant Tray A, the ultrasonic which is placed on the top cover of the water tank will measure the water left after the water sprinkler with the water pump does the irrigation process. The water level data collected were measured in terms of the height (in centimeters) of the water tank and subsequently converted to liter.

Hence, the results obtained from Table 4 and Figure 14 indicate that Plant Tray A has the capability to conserve water resources in the irrigation process through the implementation of the IoT plant monitoring and irrigation system. Water conservation stands out as a significant concern aimed at improving the efficiency and application for gardeners in plant irrigation processes. It can also be inferred that the wastage of water can be mitigated through the utilization of this system, ensuring water is supplied to the crops only when the soil moisture level drops below 70.

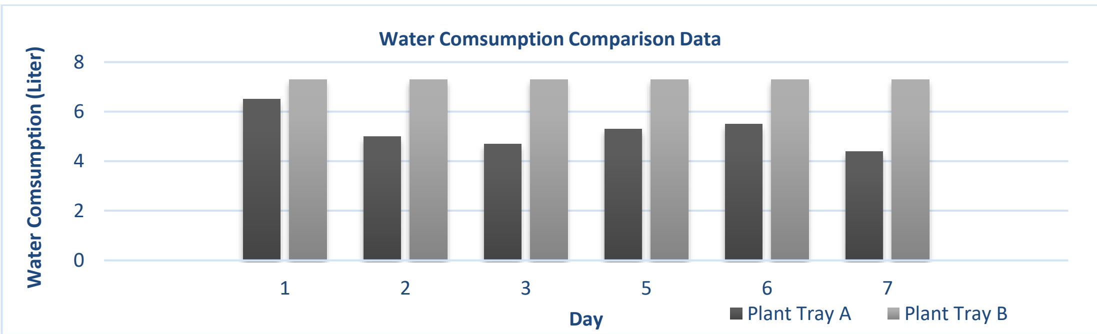

Figure 14. The graph result of water comsumption for 7 days

4. CONCLUSION

The IoT-based plant monitoring system designed and implemented in this research demonstrates a practical and reliable solution for addressing water and energy consumption issues. As outlined in the introduction, the first objective was to design and develop an IoT-based plant monitoring and irrigation system using NodeMcu ESP32, which was successfully achieved. This research focused on a small-scale crop, utilizing a hardware prototype consisting of a NodeMCU ESP32 module, a soil moisture sensor, DHT22 for monitoring surrounding conditions, an ultrasonic sensor for measuring water level in the tank, and actuators for the water pump and LCD display. The second objective has also been successfully achieved, as the system was developed to provide real-time information on the soil moisture level and surrounding conditions, including humidity and temperature. The Blynk cloud application was effectively utilized to implement the functions set in the Blynk mobile app. The mobile application empowers users to preview the soil moisture level, water level, temperature, and humidity. Finally, the variety of tests and experiments conducted to analyze the performance of this system. The experiments included the solar charging test, an assessment of the accuracy of temperature and humidity sensors, achieving an accuracy of 98% for temperature and 95% for the humidity sensor. Additionally, there was testing of the soil moisture sensor for the irrigation system, evaluating the water level sensor with a measurement accuracy error of only about 2% to 3%, and conducting a comparison of plant growth. The plants exhibited slightly better growth, approximately 9% to 10%, compared to traditional farming. Overall, the system performed admirably, but its overall performance has error of 5-10% due to sensor accuracy. To further enhance the system, future work could explore the integration of advanced sensors with higher precision to minimize errors. Implementing predictive analytics and machine learning algorithms could optimize irrigation scheduling and improve resource utilization. Expanding the system to support larger-scale farming operations and incorporating additional environmental monitoring parameters, such as light intensity and pH levels, could broaden its applicability. Additionally, improving the system's durability and scalability for diverse agricultural conditions would contribute to its adoption as a robust, eco-friendly farming solution.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Sanjoy Kumar Debnath	✓	✓								✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper.

INFORMED CONSENT

Informed consent was not required because this study did not involve human participants.

ETHICAL APPROVAL

Ethical approval was not required for this study because it did not involve human participants or animal subjects. All experimental procedures related to sensors, hardware testing, and plant materials complied with institutional safety and laboratory guidelines.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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