LOW-COST IOT-BASED INTELLIGENT SAFFRON MANAGEMENT SYSTEM

低成本物联网智能藏红花管理系统

Wai Leong PANG[1], Jieru WANG[1], Hui Hwang GOH[1], Swee King PHANG[1], Hafisoh AHMAD[1], Kah Yoong CHAN[*2]
[1] School of Engineering, Centre for Sustainable Societies, Taylor's University, Taylor's Lakeside, 47500 Subang Jaya, Selangor, Malaysia;
[2] Centre for Advanced Devices and Systems, Faculty of Artificial Intelligence and Engineering, Multimedia University, Persiaran Multimedia, 63100 Cyberjaya, Selangor, Malaysia.
Tel: +603 8312 5438.; E-mail: kychan@mmu.edu.my
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ABSTRACT

Saffron is a high-value crop that requires low growing temperatures and cannot be cultivated in equatorial climates. To address this limitation, an IoT-based Intelligent Saffron Management System (IISMS) is proposed to simulate suitable growing conditions for saffron cultivation in equatorial regions. The IISMS remotely monitors key environmental parameters, and the collected data is displayed via a mobile APP over a Wi-Fi network. The cooling system is automatically activated when the temperature exceeds 10 °C, which is the critical threshold required during the flowering phase. Similarly, the irrigation system is triggered when soil moisture drops below 70%. By providing responsive and automated crop management, the IISMS optimizes growth conditions and improves yield quality. Experimental results showed that saffron cultivated under the IISMS was healthier, taller, exhibited more green shoots, and was generally stronger compared to saffron grown under standard room conditions in Malaysia.

摘要

藏红花是一种高价值作物，需要较低的生长温度，而赤道气候无法种植。本文提出了一种基于物联网的智能藏红花管理系统(IISMS)，用于模拟赤道国家适宜藏红花的生长条件。IISMS远程监控生长条件，并通过Wi-Fi 网络将数据显示在移动应用程序中。如果温度高于10°C，则会启动冷却系统。10°C 被设定为阈值，藏红花在开花期间需要10°C的低温。当土壤湿度低于规定的70% 阈值时开始灌溉。IISMS提供响应式藏红花作物管理，优化生长条件并提高产量质量。与马来西亚室温下未采用 IISMS种植的藏红花相比，在 IISMS下种植的藏红花更健康、更高大、绿芽更多、更强壮。

INTRODUCTION

Saffron is one of the world's most expensive crops due to its rarity, labor-intensive harvesting process, and nutritional and medicinal benefits. It is native to Southwest Asia and is primarily cultivated in the Mediterranean region, including countries such as Iran, Greece, and Turkey (*Cardone et al., 2020*). Successful saffron cultivation depends on mild weather and moderate rainfall, with optimal temperatures of 23–25°C in September. Flowering of the bulbs requires mild conditions as well, with daytime temperatures around 17°C and nighttime temperatures near 10°C (*Mehmeti et al., 2024*). Saffron is a high-value crop with notable nutritional and medicinal properties. It is highly favored in the market due to its broad applications in healthcare products, pharmaceuticals, and the food industry (*Dalir et al., 2025*). The primary active compound in saffron is crocin, which is responsible for its distinctive color and aroma. Crocin also exhibits significant pharmacological effects (*Malik et al., 2024*). As a result, saffron has increasingly become a key player in the global market for premium agricultural products, with demand rising steadily each year. However, the growing demand and high market value of saffron are placing pressure on production, and current efficiency levels have not kept pace with the rapid increase in demand.

A key challenge for saffron cultivation expansion is the need for more information about optimal growing conditions. Factors like temperature, humidity, light intensity, and pH are essential for saffron growth and development. It is important to monitor these critical parameters such as moisture level, pH value, light intensity, and environmental humidity *(Narayana et al., 2024)*. Continuous observation and accurate monitoring of these variables are essential to growing saffron in the best possible conditions.

Nevertheless, the growth and production features of saffron have very high demands on such environmental conditions as temperature, humidity, light, soil moisture and so forth. This slight negligence might harm the saffron growth cycle and yield quality. Conventional planting methods still depend on manual monitoring and adjustment of the environmental conditions. These methods are costly and time-consuming, whilst becoming obsolete with climate change and environmental fluctuations. Such suboptimal approaches of management not only hamper the increase in yields but also raise the cost of production, making it hard to achieve complete economic returns for saffron production.

Temperature is one of the essential factors of the entire growing cycle of saffron. A low temperature of around 10°C is needed for saffron to start the flowering process *(Pirasteh-Anosheh et al., 2023)*. The temperature for flower formation is between 23°C to 27°C. However, the yield of the saffron will drop when the temperature is more than 30°C. It can be concluded that maintaining a suitable temperature is the key to achieving high yields in saffron cultivation.

The second important factor for saffron cultivation is humidity, particularly during the flowering and bulb stages. A study suggested that maintaining humidity at around 65.7% can significantly enhance flower production *(Iqbal et al., 2024)*. However, humidity levels become difficult to manage when rainfall is unpredictable. Controlling humidity is essential for optimizing both the quality and yield of saffron. Uncontrolled humidity levels can negatively affect plant health and reduce overall yield.

The growth and development of saffron are significantly influenced by light. According to research, the yield and quality of saffron can be significantly influenced by properly adjusting the lighting. The red-to-blue light ratio of 3:2 with a photosynthetic photon flux density of 200 $\mu molm^{-2}s^{-1}$ has been found to enhance stigma yield and improve nutritional content *(Kang et al., 2022)*. However, while high light intensity can promote photosynthesis and leaf growth, it may also reduce both the quantity and quality of saffron stigmas (*Zhou et al., 2022*). These findings suggest that optimizing both the light spectrum and intensity is essential for improving saffron output and quality.

Saffron is highly sensitive to soil pH, which significantly affects microbial activity, nutrient availability, and overall plant health. Soil pH, which ranges from 0 to 14, indicates the acidity or alkalinity of the soil. Values below 7.0 signify acidic conditions, while those above 7.0 indicate alkalinity. Most crops thrive in a pH range of 6.0 to 7.5, which supports optimal root development and nutrient absorption. Saffron performs best in neutral to slightly acidic soils, with an ideal pH range of 6.0 to 8.0 *(Kumar et al., 2022)*. This pH range ensures the availability of essential nutrients such as nitrogen, phosphorus, potassium, and various micronutrients, supporting the healthy development of saffron bulbs and sprouts.

Numerous projects were carried out to collect and analyze environmental data in order to enhance agricultural yield and productivity. One such initiative proposed a portable system that monitors air humidity, temperature, and soil moisture using sensors, with the collected data used to control irrigation for vegetable crops *(Penchalaiah et al., 2021)*. Sensor networks have also been employed in precision agriculture to optimize crop yields and resource efficiency *(Sanjeevi et al., 2020)*. A real-time remote management and monitoring system was introduced for greenhouses, utilizing wireless networks to track plant conditions *(Bersani et al., 2022)*. The Internet of Things (IoT) was used to monitor 14 environmental parameters in order to increase the crop yield *(Aditya et al., 2024)*. Another IoT-based system was designed to capture and analyze environmental variables such as humidity, indoor and outdoor temperature, soil moisture, and carbon dioxide concentration in tomato plantations *(Ge et al., 2022)*. Additionally, a prototype equipped with Bayesian predictive networks was proposed to respond to sensor feedback on plant growth metrics, water levels, pH, light intensity, and humidity *(Kocian et al., 2020)*. All collected data and prototype operations were stored in the cloud, highlighting the potential of IoT technologies in advancing sustainable agriculture.

Intelligent and automated planting management strategies are urgently needed to enhance the yield of saffron plantations. IoT technology presents promising opportunities to address this challenge. The integration of IoT with agriculture has greatly advanced precision farming practices by improving crop monitoring and resource management *(Dhanaraju et al., 2022; Haziq et al., 2022; Leao, 2024; Lokman et al., 2024)*. Furthermore, IoT has demonstrated strong potential in regulating microclimate conditions to enhance crop yield and quality *(Pangave et al., 2023)*. An intelligent planting system equipped with IoT sensors and automated control mechanisms can continuously collect environmental data such as temperature and humidity. This enables real-time monitoring and precise regulation of the saffron growing environment, optimizing conditions for plant development. As a result, such systems not only improve crop yield and quality with high efficiency but also provide a scientific foundation for data-driven saffron cultivation.

Existing research has yet to propose a smart and reliable IoT system specifically tailored for saffron cultivation. Due to the unique environmental requirements of saffron, conditions that are particularly difficult to achieve in equatorial regions, there is an urgent need for a dedicated IoT-based intelligent management system. To address this gap, the IoT-Enabled Smart Saffron Management System (IISMS) is proposed. This system is designed to monitor and control four critical environmental parameters essential for saffron growth: temperature, humidity, light intensity, and soil pH.

MATERIALS AND METHODS

The proposed IISMS provided a real-time monitoring and intelligent control of the saffron planting environment to meet the strict requirements of saffron for temperature, humidity, light and soil moisture. The architecture of the IISMS system is shown in Figure 1. IISMS consists of four main systems, i.e., 1) a lighting system, 2) an irrigation system, 3) a cooling system, and 4) a soil monitoring system. The lighting system supplies the artificial light source through LED. A water pump is equipped in the automatic irrigation system. A semiconductor cooling module is installed to control the temperature. A monitoring system is used to monitor the soil's parameters. The IISMS provides real-time monitoring and automated management of saffron growth environments.

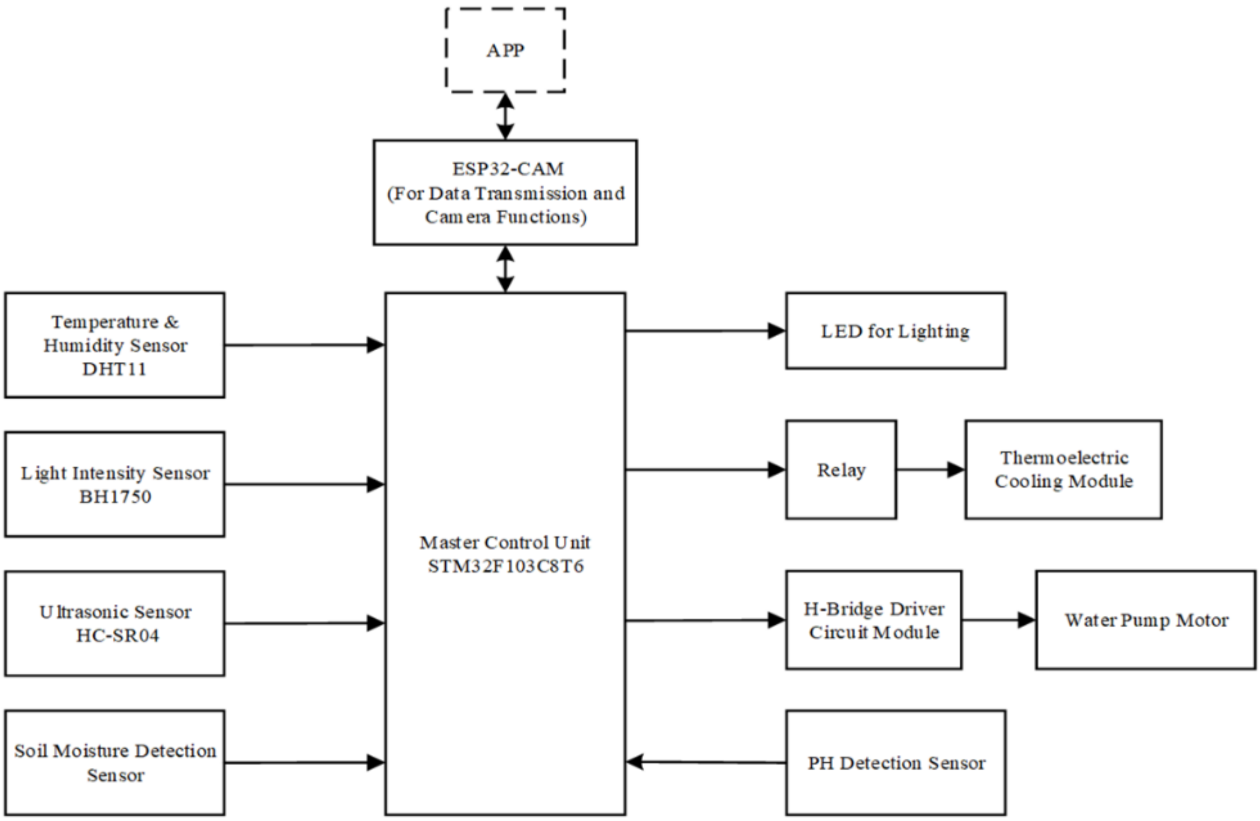

Fig. 1 – The System Architecture of IISMS

The STM32 (STM32F103C8T6) microcontroller is the core controller of IISMS. The STM32 microcontroller is used to control and process the data collected. It is responsible for reading different sensors and controlling the actuators based on a pre-configured threshold so that saffron in its growing environment finds a suitable environment. The STM32 microcontroller offers a wide range of input/output (I/O) interfaces, enabling efficient integration and operation of various sensors and actuator modules. It serves as the central controller of the system, coordinating all sensors and actuators to perform data acquisition, logical processing, and control output. With its high performance, low power consumption, and rich peripheral interfaces, the STM32 is well-suited to meet the system's requirements for handling multiple sensor inputs and controlling multiple actuators simultaneously.

IISMS used a BH1750 light sensor (Figure 2) to measure the light intensity of the environment and provide the system with reliable light data, thereby assisting in automated light control. BH1750 is a light sensor that has I2C communication to output the digital value of ambient light intensity and this will reduce the overhead in data processing. It has high sensitivity and stability. It can give accurate measurement results under different light conditions, which is very suitable for monitoring the saffron growth environment. When the system detects that ambient light intensity drops below the predefined threshold, the IISMS sends a high-level signal to the General Purpose Input/Output (GPIO) to activate the LED fill light. This ensures that saffron plants receive adequate illumination under low-light conditions, supporting healthy growth. Once the light conditions return to normal, the system deactivates the LED light. The LED light operates at a voltage of 3.3 V. The design of the lighting system is simple and the power consumption is low. The LED has a long service life and low power consumption, which is suitable for long-term continuous operation to meet the needs of plant growth.

The soil moisture sensor was used to track the soil moisture level instantly (Figure 3). The sensor is used to measure the moisture content in the soil where saffron is cultivated. It detects the level of dryness or wetness, allowing the system to automatically regulate irrigation based on real-time soil moisture data. The output of the sensor is an analog signal, which is connected to the analog-to-digital interface of the STM32 to achieve real-time measurement of soil moisture. The sensor module was equipped with a potentiometer, and the user can configure the threshold by adjusting the potentiometer to adapt to different soil moisture requirements. The system automatically starts the water pump for irrigation when soil moisture is less than the threshold value to keep humidity conditions in the range.

The pH detection sensor (Figure 4) was used to measure the pH value of the soil. Accurate monitoring of the pH value is essential for the healthy growth of saffron, so this sensor module is used to measure the pH value of the soil in real time. The sensor transmits data to the main control unit through serial communication. The pH sensor will measure the pH of the soil and give the user the health status of the soil to ensure that the soil is well-suited for saffron growing.

The DHT11 temperature and humidity sensor (Figure 5) was used to obtain the current environmental temperature and humidity data, which provides the basic information for temperature–humidity control. The DHT11 sensor can provide relatively stable temperature and humidity data. The sensor uses a single bus protocol for data transmission and can read data by occupying a GPIO pin of the microcontroller.

The IISMS automatically activates the semiconductor cooling system, LED lights, and water pumps based on predefined thresholds to regulate temperature, supplement light, and provide irrigation. The ESP32-CAM module collects and transmits real-time images and environmental data to a mobile. The APP (Figure 6) provided users with a data display to monitor the saffron growth. Users can remotely view the key parameters such as temperature and humidity, light intensity, soil moisture and pH value of the environment through the APP.

Fig. 2 – BH1750 light sensor

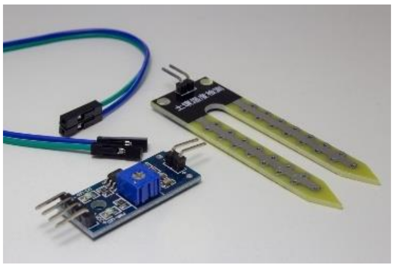

Fig. 3 – Soil moisture sensor

Fig. 4 – PH sensor

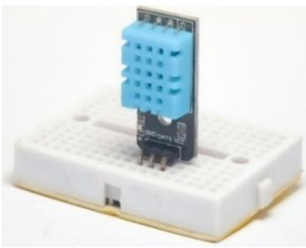

Fig. 5 – DHT11 temperature and humidity sensor

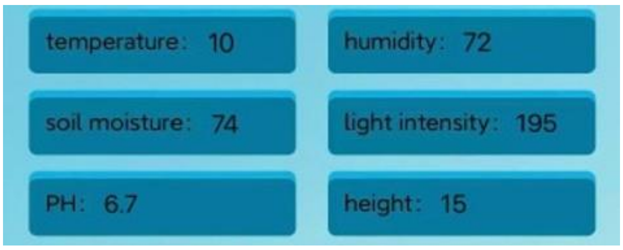

Fig. 6 – The mobile APP of the IISMS

A relay was used to control the semiconductor cooling module shown in Figure 7. It began to cool down the temperature as soon as the thermostat detected that the temperature was above the threshold value. A HC-SR04 ultrasonic sensor was used to measure saffron growth height and provide data support for crop growth monitoring. The system can monitor the height changes from time to time to record and indicate saffron growth for subsequent planting management and data analysis.

The system used the AMS1117-3.3 voltage regulator chip to step down the input voltage to a stable 3.3V ensuring reliable operation of the STM32 microcontroller. To minimize power supply noise and stabilize the output voltage, decoupling capacitors of 100 μF and 10 μF were connected at the input of the voltage regulator circuit. These capacitors effectively filtered out voltage fluctuations and contributed to a smooth and consistent power supply.

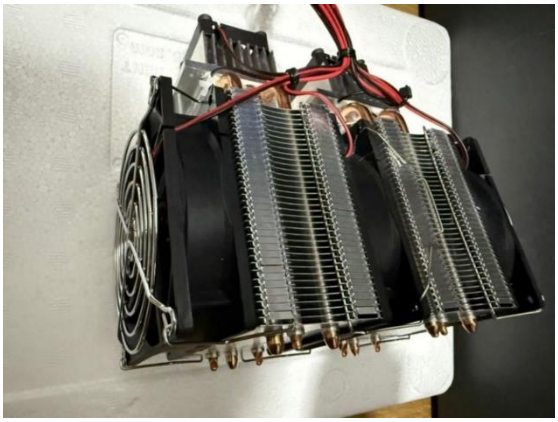

Fig. 7 – The cooling module used in IISMS

The proposed IISMS provides a customized solution designed to simulate optimal environmental conditions for saffron cultivation. Threshold values for key parameters were carefully selected based on the physiological requirements of the saffron plant. The soil moisture threshold was set at 70%, representing the ideal hydration level to support bulb development and flowering while avoiding waterlogging. The temperature threshold was set at 10°C, a critical value for initiating the flowering phase of saffron.

An extensive experiment was carried out to evaluate the performance of IISMS. The experiment was conducted indoors using two pots of saffron plants. Saffron was planted in both pots under identical initial conditions and cultivated in parallel. One pot was cultivated using the IISMS inside a styrofoam box, which actively monitored and regulated environmental parameters. The other pot served as a control and was grown under standard indoor, air-conditioned room conditions with an artificial light source in Malaysia. A general-purpose fertilizer was used in this experiment. IISMS was exposed to varying environmental conditions to test its responsiveness and accuracy. The LED fill light was triggered when ambient light intensity dropped below the predefined threshold, and deactivated once normal lighting conditions were restored. Similarly, the cooling module was activated when the temperature exceeded 10°C. The irrigation system was programmed to initiate when soil moisture fell below 70%, which is the optimal level for saffron bulb development without risking overwatering. The experiment was carried out with the styrofoam box closed to control a low temperature, and the LED light was turned on to provide a light source. The experiment was conducted over a one-week period, during which environmental data and plant responses were continuously recorded. The results were presented in the next section.

RESULTS

The extensive experimental test was carried out through the testbed shown in Figure 8.

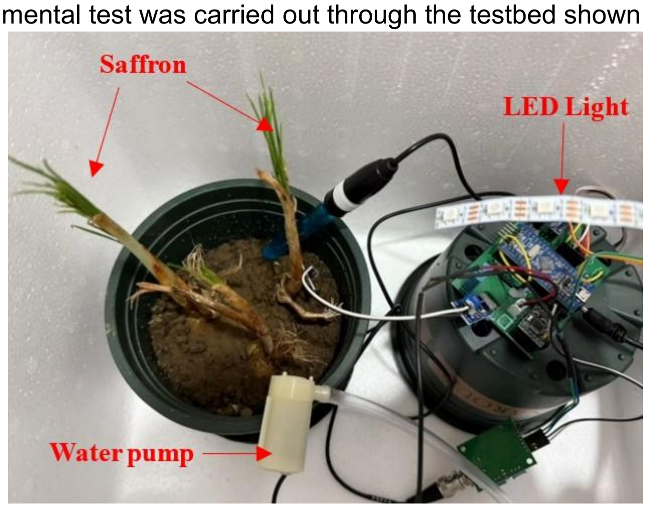

Fig. 8 - The System Architecture of IISMS

The testbed was designed for small-scale saffron cultivation. The saffron plant was cultivated in a pot filled with soil. An automated water pump was connected to the pot to ensure consistent irrigation, while an LED light strip was installed above the plant to provide artificial lighting, simulating optimal sunlight conditions. The LED light was turned on for 8 hours daily, since the experiment was conducted inside a closed Styrofoam box. The IISMS was activated at the beginning of the experiment to monitor and regulate environmental parameters.

Figure 9 illustrates the soil moisture level of the testbed. Initially, the moisture level started at around 60%. The IISMS detected a drop in soil moisture, and the irrigation system was activated, maintaining the moisture level at approximately 70% over the following hour. The moisture level reached around 100% by day 2 due to the excess water that was supplied to the saffron plant, resulting in a high moisture percentage. After this peak, the moisture level dropped and stabilized around the 70% reference line. The result showed that IISMS effectively maintained the target soil moisture level throughout the remainder of the observation period.

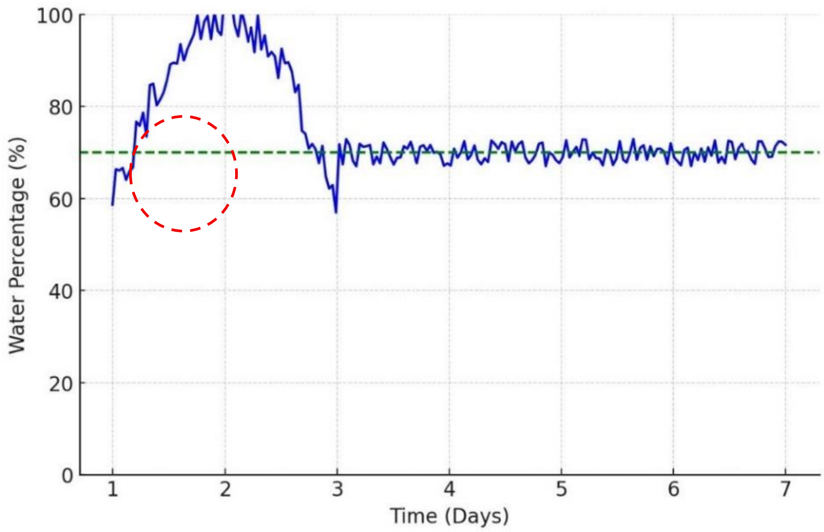

Fig. 9 – The soil moisture levels measured over a week

Figure 10 illustrates the variation in temperature over 7 hours. The temperature initially remained high at around 35°C but dropped sharply to approximately 10°C after 2.5 hours, as a result of the IISMS activating the cooling system. The temperature stabilized with minor fluctuations for the remainder of the 7-hour observation period. The IISMS was designed to automatically activate the cooling module when the temperature exceeded the preset threshold of 10°C and to deactivate it once the temperature returned to the threshold. The temperature remained stable at 10°C over a period of 7 days. However, the graph was presented over a 7-hour timespan to highlight the initial temperature changes during the early stage of the experiment. This shows the effectiveness of the IISMS in regulating temperature and provides the desired temperature level for saffron cultivation.

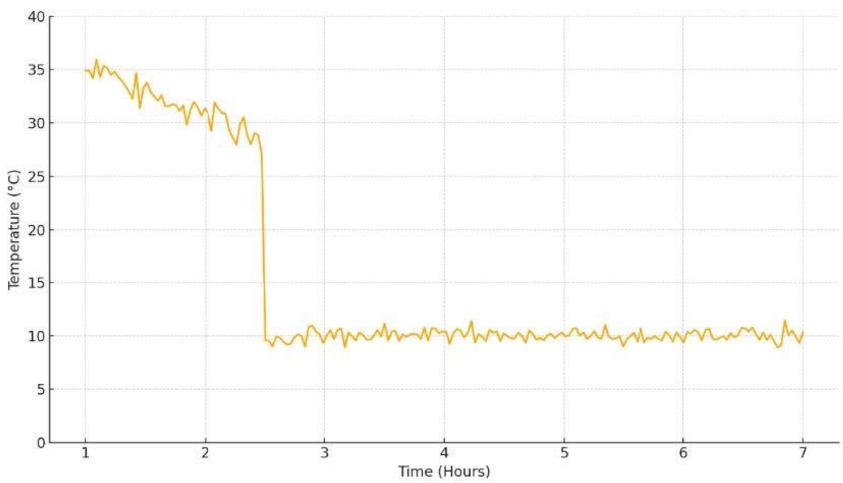

Fig. 10 – The temperature values measured over a week

Figure 11 illustrates the change in pH value over 7 days. The pH level started at approximately 7.2 and gradually declined to around 6.6 by Day 7. An annotation on the graph noted that the pH value dropped by 0.6 over the week. The pH dropped from 7.05 to 6.6 over the week, and several peaks were observed in the collected data. These fluctuations were primarily caused by the uneven distribution of fertilizers through the irrigation system's water flow. This pattern demonstrated that soil pH was directly influenced by soil fertility and irrigation practices, highlighting the importance of consistent monitoring and controlled nutrient delivery to maintain optimal growing conditions.

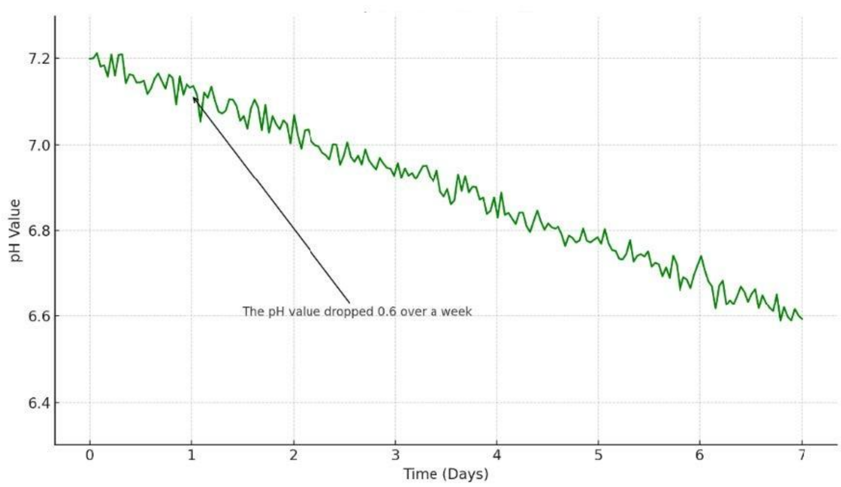

Fig. 11 – The pH values obtained over a week

Figure 12 shows two pots of saffron planted in parallel, one pot was planted with the IISMS, and the other was grown under standard indoor conditions. As shown in Figure 12, the saffron grown with the IISMS appeared healthier, taller, with more green shoots and stronger compared to the saffron cultivated without IISMS under room conditions, with fewer and less vigorous shoots. This indicated that the IISMS successfully simulated suitable growing conditions for saffron in Malaysia.

Fig. 12 – The growing conditions of saffron plants with and without IISMS

CONCLUSIONS

The proposed IISMS successfully simulates optimal growing conditions for saffron, demonstrating high accuracy and stability in environmental monitoring. All sensors performed reliably under varying environmental conditions, delivering accurate data that supports the system's automatic control functions. The IISMS effectively monitors key environmental parameters, such as temperature, humidity, light intensity, and soil pH, in real time and automatically adjusts these conditions to promote healthy saffron development. Additionally, it enables users to remotely access environmental data and respond promptly to abnormal conditions. However, some areas for improvement were identified. The DHT11 temperature and humidity sensor exhibited a delayed response during rapid environmental changes, which affected the real-time accuracy of the readings. Despite this limitation, the IISMS performed well across environmental monitoring, automatic adjustment, and remote control functionalities, validating its feasibility and potential for agricultural applications. Future improvements could include integrating solar energy to offset the high power consumption of the cooling system. Moreover, deploying the IISMS in greenhouse environments would allow assessment of its performance in managing larger-scale cultivation. The system's adaptability also suggests potential for application in other crop management scenarios, enhancing its flexibility and scalability for broader agricultural use.

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