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EVALUATION OF AN IOT-BASED SMART IRRIGATION SYSTEM FOR GROWTH OPTIMISATION OF EGGPLANT (*SOLANUM MELONGENA*) UNDER RAIN SHELTER

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Efficient irrigation is vital for crop cultivation, particularly for eggplant (*Solanum melongena*), which ranks as Malaysia's fourth most important vegetable crop. This study evaluates the effectiveness of an Internet of Things (IoT)-based smart irrigation system in enhancing eggplant growth under rain shelter conditions. The system monitored environmental and soil parameters, including air temperature, relative humidity, soil pH, electrical conductivity (EC), and soil moisture and temperature, enabling remote irrigation adjustments to optimise plant health and resource use. Plant growth and environmental data were collected using both manual and IoT-based monitoring systems. IoT sensor measurements were calibrated against manual sensors at specified intervals. Results revealed a 32-day time series of sensor data and calibration curves, with R-squared values ranging from 0.78 to 0.98, indicating strong agreement between manual and IoT measurements. Eggplants irrigated using the IoT system showed significant improvements in plant height, leaf length, leaf diameter, stem thickness and root biomass compared to manual irrigation. The IoT-based monitoring system also produced reliable and consistent measurements, supporting its accuracy and applicability. In conclusion, the IoT-based smart irrigation system enhanced eggplant growth, reduced resource wastage, and improved overall efficiency, highlighting its potential for sustainable agricultural practices.

Keywords: IoT sensors; fertigation; precision agriculture; sustainable farming; artificial intelligence; food production

The Internet of Things (IoT) represents a transformative shift in technology, reshaping the interaction between humans and their surroundings, particularly through sensor-based systems. It is one of the fastest-growing technological revolutions, rapidly transforming industries and everyday life (Witczak and Szymoniak, 2024). In the context of agriculture, the IoT revolution has a significant impact as it integrates sensors, connectivity, and intelligent data processing to revolutionise the management of crops (Vitali et al., 2021), soil health (Ramson et al., 2021), water monitoring (Zulkifli et al., 2022), and environmental conditions (Eze et al., 2025; Saad et al., 2020). In agriculture, optimising water management is crucial to ensure optimal plant growth (Saad et al., 2020). For crops grown under shade, such as greenhouses, water and fertiliser distribution is carefully controlled and specifically tailored to meet their specific needs. This helps maintain consistent soil moisture levels and provides plants with the hydration required for growth. Traditionally, irrigation systems involve scheduled application either by manual control or by timer, but more recent developments employ IoT-based smart irrigation, which utilises various sensors for monitoring. This innovative approach is designed to ensure crops receive water efficiently (Levidow et al., 2014), and minimise water wastage (Shobana and Nithya, 2022).

Previous research utilised an IoT-based smart irrigation system involving various sensing elements and system protocols, aiming to optimise water usage. According to García et al. (2020), the most common parameters to be monitored in the soil are soil moisture, temperature (Zhang et al., 2017), pH (Krishna et al., 2017), its nutrients (Raut et al., 2018), and electrical conductivity (EC) (Zamora et al., 2019). For weather monitoring, air temperature and humidity, which influence soil water evapotranspiration, are the two most frequently observed parameters. Other applications of IoT involve monitoring the plant using a web camera and image processing analysis to detect plant changes caused by disease infestation, as described by Lakshmi and Gayathri (2017). In a hydroponic system, integration of IoT enhances the yield and plant growth by monitoring the crucial parameters such as EC, pH levels, temperature, and humidity (Aurasopon et al., 2024). In terms of hardware, Arduino boards are the most widely utilised nodes in developing low-cost systems, typically supported by WiFi (Singh et al., 2019; Chieochan et al., 2017). However, most applications of the IoT-based irrigation systems have focused on system development rather than system evaluation and effectiveness. Therefore, this study proposes monitoring the output of the IoT-based data and comparing it with manual measurements to evaluate the system in enhancing the growth of a full cycle of eggplant.

Material and Methods

Study area

This study was conducted at the Permanent Food Production Park (TKPM) Inderapura, in Pahang, with a total land area of 0.41 hectares. The TKPM land was under the management of the Department of Agriculture, Kuantan, with the engagement of various entrepreneurs utilising the land and facilities provided in the area. The TKPM Inderapura entrepreneurs are focusing on planting various plants, including eggplant, cucumber, chilli, sweet potato, and other crops that are in demand for local consumption and export. It provided a controlled environment supported by the government and serves as an important hub for agricultural research and development. The selected plot for this study is equipped with a rain shelter and an IoT smart irrigation system for the entrepreneur. The grower utilised the hanging fertigation system technology, with each bag connected with irrigation tubing and a nipper connected from the main pipe and fertiliser tank. The hanging polybag method was designed to reduce the risk of being affected by flash floods during the rainy season since the area was situated in a prone area to flooding. A total of 477 polybags of eggplants were cultivated across nine rows of the study area, with each row consisting of 53 polybags. Each polybag contains planting media such as cocopeat. A total of 30 polybags were chosen randomly, as illustrated in the schematic diagram in Fig. 1. The selection of the polybags ensures the soil monitoring samples are taken across the area of the irrigation scheme.

Manual monitoring of plant growth and soil parameters

The irrigation system efficiency was monitored using a manual method at various polybags, as depicted in Fig. 2. The soil EC and temperature were manually determined using an EC8801 probe (Fig. 2a), while soil moisture and pH were measured with a VT-05 Soil meter probe (Fig. 2b). These manual measurements were taken at 30 random polybags within the plot, as depicted in Fig. 1b, to ensure the water reached the end of the irrigation line. The measurement was used to calibrate the sensors for the plant monitoring system. Plant growth parameters such as plant height (Fig. 2c), leaf length (Fig. 2d), and width (Fig. 2e) were measured at each week with an average of three measurements per plant to monitor the plant development under this IoT smart irrigation system.

IoT-based smart irrigation system

The IoT-based smart irrigation system integrates the components of hardware from sensors located within the greenhouse area with a microcontroller to continuously monitor and collect environmental data. This real-time data was read from the sensors and recorded in a cloud database over a Wi-Fi connection. Irrigation was scheduled according to Table 1 to ensure the maximum growth of the plant according to the growing stage. The eggplants

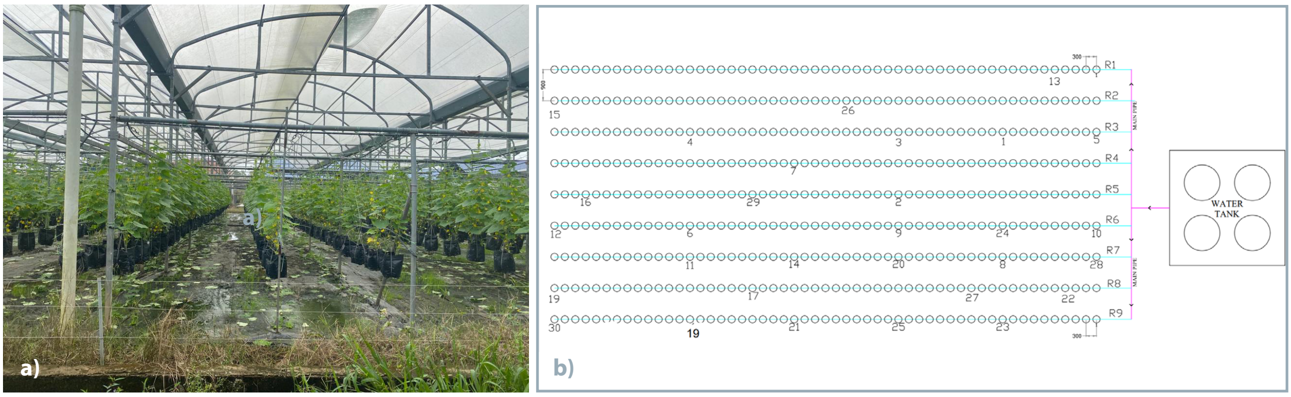

Fig. 1 The selected
a) Plot area; b) Schematic layout and sampling of the polybags

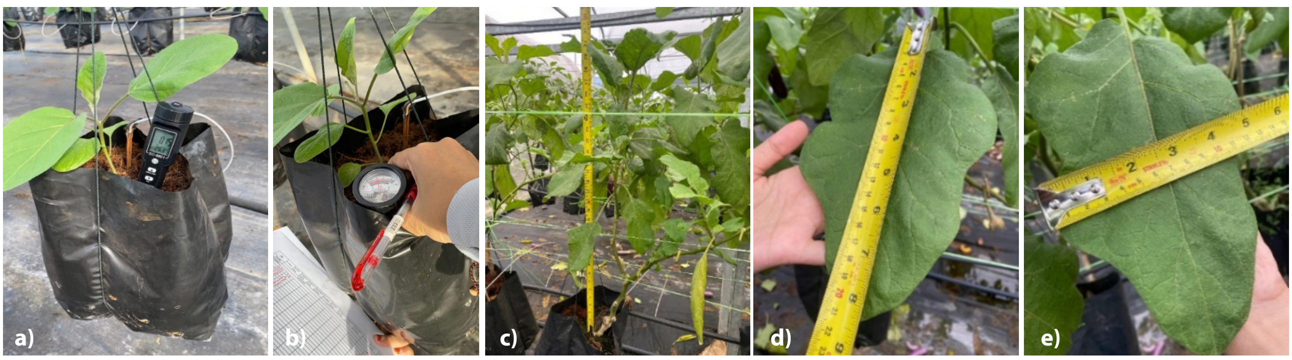

Fig. 2 Manual measurements of
a) electrical conductivity and temperature measurement using EC-8801 probe; b) pH and soil moisture measurement using VT-05 Soil pH meter probe; c) plant height; d) leaf length; e) leaf width

Table 1 The irrigation schedule

No	Time	Operation	Duration (s)
1	3:00 am	fresh water	240
2	9:00 am	fertiliser A&B	150
3	10:00 am	fertiliser A&B	120
4	11:00 am	fertiliser A&B	120
5	12:00 pm	fertiliser A&B	250
6	12:15 pm	pump dosing of mixing fertiliser A&B and transfer to tank	
7	12:30 pm	transfer to tank	360
8	1:00 pm	fertiliser A&B	150
9	2:00 pm	fertiliser A&B	120
10	3:00 pm	fertiliser A&B	120
11	4:00 pm	fertiliser A&B	250
12	5:15 pm	pump dosing of mixing fertiliser A&B a	
13	9:00 pm	fresh water	150

were irrigated with fertilisers A and B eight times per day, with an additional two times of freshwater flushing. The monitored schedule enables the grower to halt irrigation based on the weather and soil parameters monitored by the system. For example, the frequency of irrigation will be less than scheduled during rainy days as compared to sunny days. On sunny days, temperature is high, which leads to high evapotranspiration, and the soil dries up quickly compared to rainy days. Therefore, this systematic schedule ensures that the plants receive a balanced mix of water and nutrients throughout the day.

System hardware

The IoT-based irrigation system was designed and developed by the Department of Agriculture in collaboration with an engineering company. The irrigation system hardware comprised a mixing tank for liquid fertilisers A and B, integrated with water level, EC, and pH sensors to monitor the solutions inside the tank. An IoT station equipped with a display panel was used to present the real-time data collected from the sensors, while a weather station monitored the environmental parameters such as temperature and relative humidity within the greenhouse. The irrigation pipe network was connected to a water tank and nutrient dosing pump with automatic water control and scheduling functions based on a threshold detection algorithm. Figure 3 depicts the schematic diagram of the overall irrigation system.

An industrial RS485 4-in-1 sensor was used to monitor soil parameters (moisture, EC, pH, and temperature), while a simple weather station (RK900-01) monitored the air relative humidity and temperature in the shade. At the same time, the nutrient mixing tank was equipped with three different sensors to monitor the water level (RKL-01), pH (RK500-12), and EC value (RK500-13). The hardware components were integrated with an STM32 microcontroller to read sensor data and store it in a database via Wi-Fi. The irrigation pump was turned on or off based on the irrigation schedule. The water pump was controlled using a 2-Hp active-high relay. The EC value in the fertiliser tank was monitored as an indication of fertiliser application.

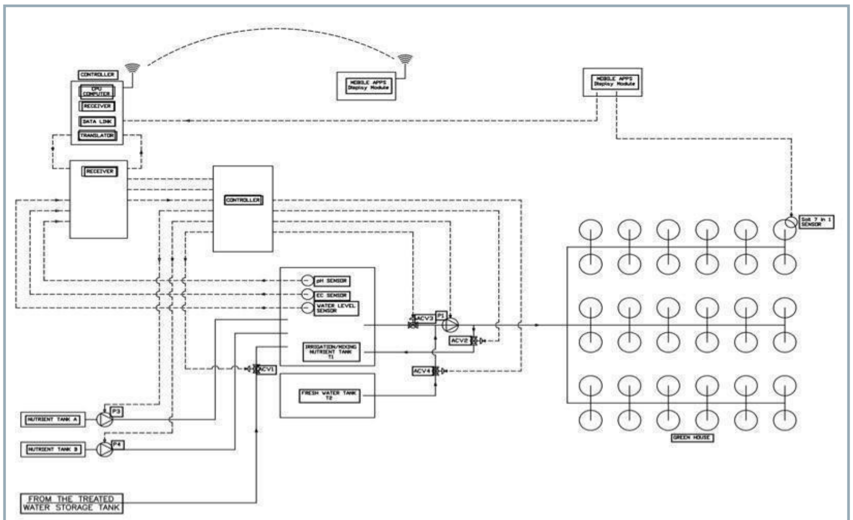

Fig. 3 Schematic diagram of the overall irrigation system equipped with IoT-based sensor monitoring

System software and control

Data collected from the sensors were stored in an application database and displayed on a panel, as well as on a mobile phone via its dedicated apps. The application served as the system's server-side. Real-time data was recorded hourly and consistently stored in the cloud using Long Range (LoRaWAN) technology, which operates on minimal battery power.

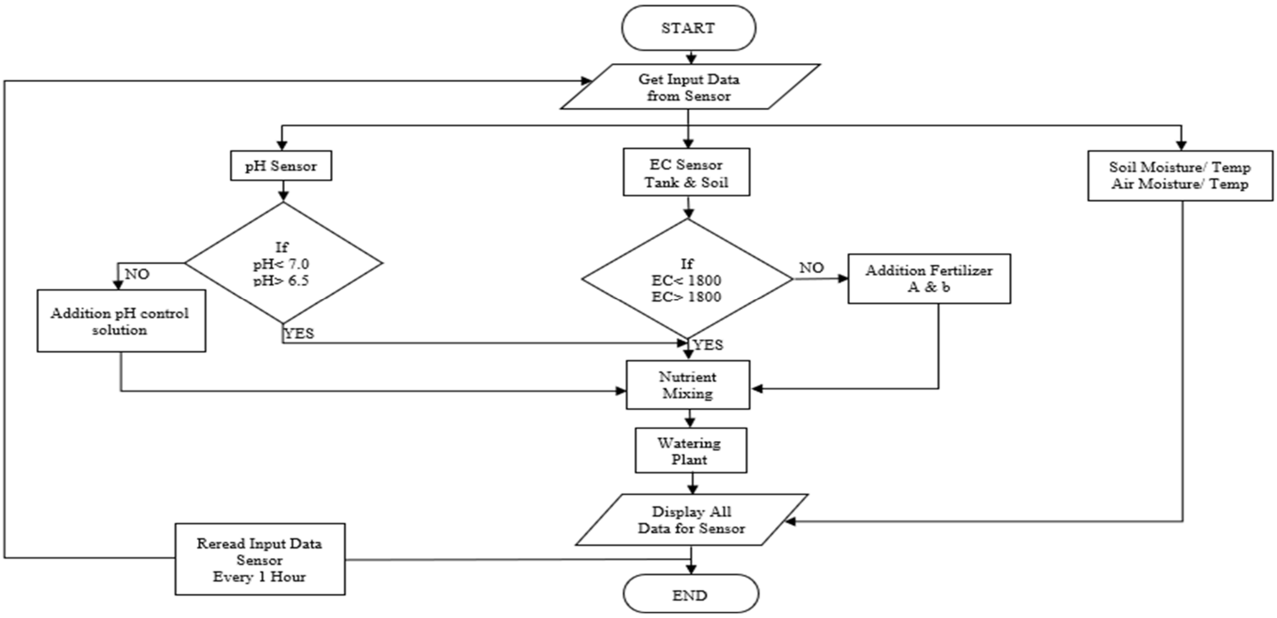

Fig. 4 Flowchart of the irrigation system control

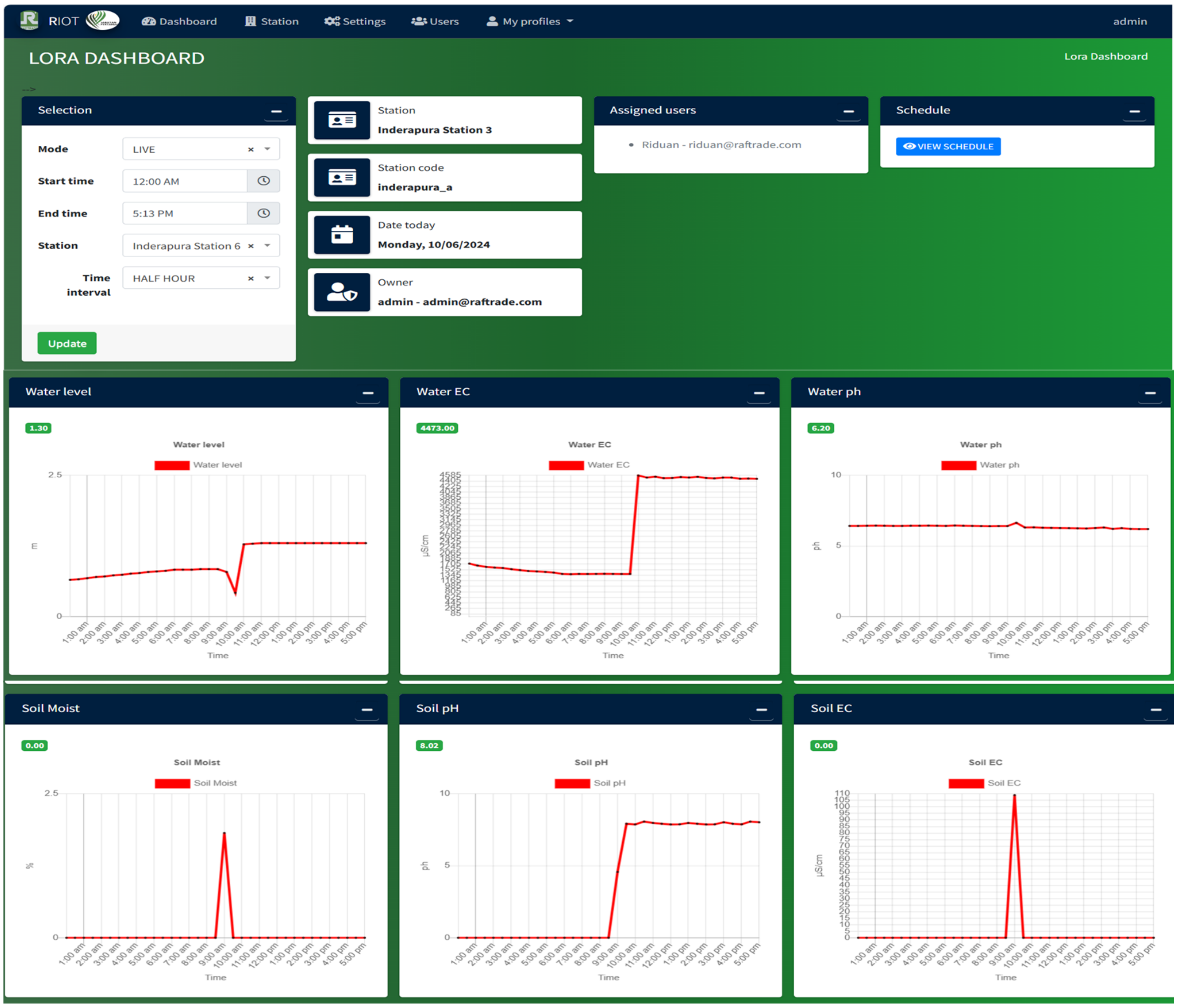

Fig. 5 Dashboard for real-time monitoring of eggplants (*Solanum melongena* L.)

The programmed microcontroller pumped the fertilisers A and B into the mixing tank every week at 1440 ppm. The system decides to irrigate the polybags based on the information collected from the sensors provided, as shown in Fig. 4. The flowchart highlights the role of the sensors in maintaining optimal soil conditions and ensuring the system operates effectively.

The system begins by collecting input from various sensors. Specifically, a pH sensor monitors the mixing tank to ensure levels remain between 6.5 and 7.0. If the pH falls outside this ideal range, the system automatically adds a pH adjustment solution. Next, the system evaluates the electrical conductivity (EC) of the soil mixture. If the EC value meets the required threshold, the solution is directed to the nutrient-mixing irrigation tank. Otherwise, it is recirculated to the fertiliser A and B tanks for adjustment. Once the mixture reaches the desired composition, it is delivered to the eggplant plots. Soil sensors installed in polybags within the plots monitor local conditions. If soil moisture falls below the target level, the water pump and mixing tank are activated to supply irrigation. If the EC reading is outside the acceptable range, the mixture is redirected to the nutrient irrigation tank for further adjustment. This demonstrates how real-time data collection and analysis support efficient water usage and promote healthy plant growth.

IoT system monitoring dashboard

The dashboard can be accessed at the website provided by the company. From the dashboard (Fig. 5), the user can select between three modes, such as Live, Yesterday, and Archive, to view data from different time frames. This feature is particularly useful if the grower is unable to physically visit the field, as they can remotely access and manage the irrigation schedule using this dashboard. The graph illustrates the water level readings, pH level, and EC value over time within the mixing tank. It also shows the temporal variations of soil moisture, EC values, and pH level in the eggplant polybags. This helps farmers keep track of the water availability and soil condition before and after irrigation. Monitoring all these values in the mixing tank is crucial for ensuring the water quality is suitable for crop health.

Results and Discussion

Environmental parameters monitoring

Figure 6 shows the average environmental parameters measured by the weather station in the shaded planting area. At the start of the experiment, the temperature peaked at 36 °C before dropping to 28 °C; it then stabilised at 32 °C from day 8 to day 28. The maximum air temperature of 36 °C was recorded at the end of the experiment. Relative humidity exhibited an inverse relationship with air temperature: it dropped to approximately 65% during sunny periods, while reaching saturation at lower temperatures, often coinciding with rainfall. This pattern is consistent with typical tropical climates and reflects diurnal variations. However, measurements were limited by sensor calibration accuracy, particularly at extreme values, where potential errors may have distorted the recorded environmental conditions.

Soil parameters

Figure 7 shows the results of the average mean value of the measured parameters obtained from manual sampling and automated recording by the IoT system over 32 days of the experiment. Figure 7a shows the manual measurement of the EC value exhibits sharp fluctuations between days 8 and 24, with a notable drop near day 20. In contrast, the EC value recorded by IoT remained relatively stable around 0.2 µS·cm-1 throughout the period. Figure 7b illustrates greater variability in soil temperature during the early manual sampling, with sharp peaks that suggest inconsistencies likely due to sampling times and human error. Both datasets reflect similar overall temperature ranges, with IoT data appearing more refined and consistent. Meanwhile, the pH (Fig. 7c) and soil moisture (Fig. 7d) measurements displayed steadier patterns in both the manual and IoT monitoring, with comparable temporal trends responsive to environmental changes. Overall, IoT-based monitoring systems provided smoother transitions and higher temporal resolution, offering more consistent readings than manual methods. The superior reliability of the IoT-based system stems from automated calibration and continuous monitoring, which reduce human error and capture environmental dynamics more effectively. In contrast, manual sampling is limited by discrete measurement intervals and susceptibility to operator error. Its inability to capture rapid changes explains the fluctuations observed in the data.

Consistent with the observations in Fig. 7, the calibration between

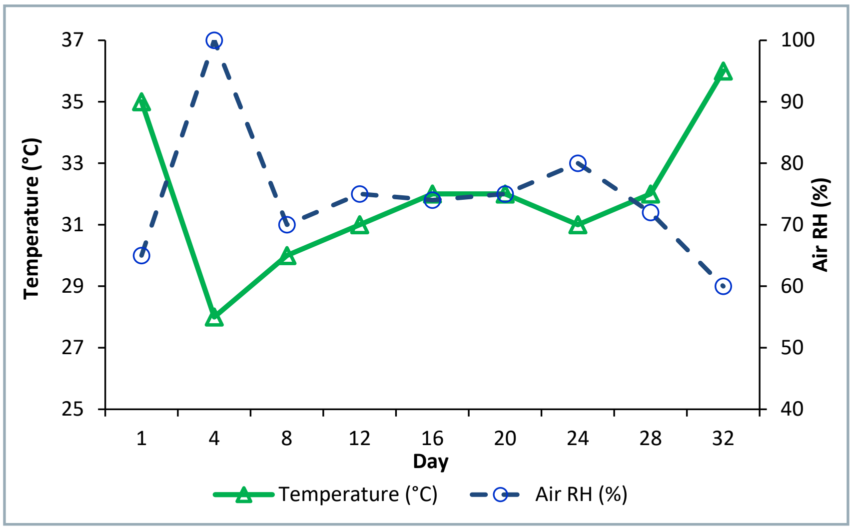

Fig. 6 Average temperature and relative humidity from the weather station captured by the IoT system

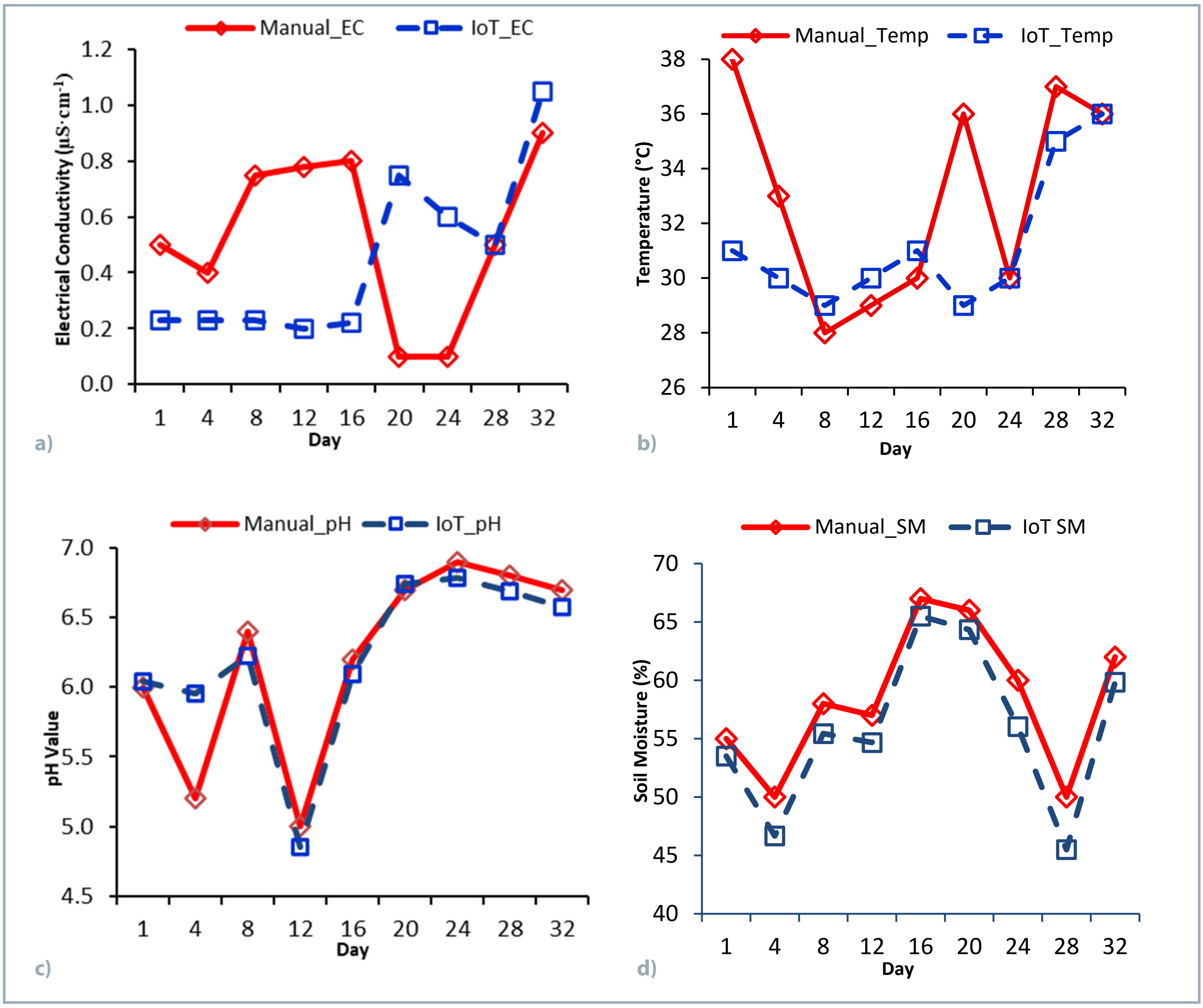

Fig. 7 The manual and IoT measurement
a) soil EC; b) soil temperature; c) soil pH; d) soil moisture

manual and IoT-based data shows a strong correlation, with the highest R2 of 0.9848 recorded for soil moisture, as shown in Table 2. Although the EC value yielded a lower R2 of 0.7799, the results overall indicate a high level of agreement between manual and IoT measurements.

Plant growth parameters

Plant height, leaf length and width

Figure 8 shows the plant growth parameters from day 1 to day 32 of the observation period. The plants have shown significant growth in plant height (16 cm to 85 cm), leaf length (16.4 cm to 26.1 cm), leaf diameter (11.5 cm to 18.0 cm), and stem thickness (5.58 mm to 13.25 mm) when irrigated using this IoT system. The plant height has shown a very rapid growth between day 12 to day 20, showing a transition from the vegetative stage to a more vigorous growth stage. At this stage, plants show increased photosynthetic capacity and nutrient uptake, reflecting a concurrent increase in leaf size. The slight decrease in leaf length and diameter on day 32 might suggest the onset of resource reallocation as the plant matures, potentially preparing for flowering or fruiting. Overall, the data align with typical growth patterns of eggplants, highlighting substantial vegetative growth during the mid-to-late experimental stages (Mahamad et al., 2022).

Table 2 Calibration between manual and IoT-based monitoring data

No	Soil parameters	R^2	Calibration curve
1	EC	0.7799	Y = -0.6675x + 0.6472
2	temperature	0.8076	Y = 0.7023x + 9.1985
3	pH	0.8268	Y = 0.7908x + 1.3026
4	moisture content	0.9848	Y = 1.1123x - 9.1636

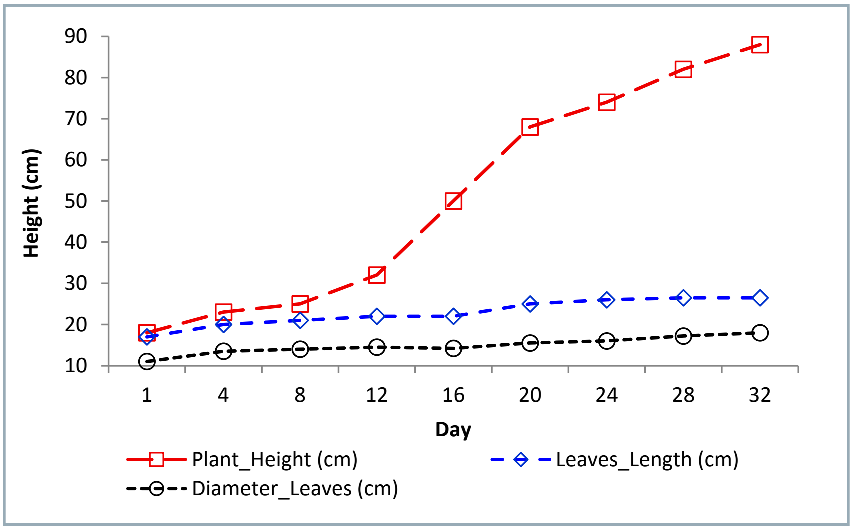

Fig. 8 Plant growth parameters (plant height, leaf diameter, and leaf length)

Fig. 9 Plant root biomass

Plant root biomass

The root biomass of eggplants was measured as dry weights at the end of a 32-day experimental period. As shown in Fig. 9, values ranged from 15.5 g to 42.0 g, with the highest observed in S5 (42 g) and the lowest in S30 (15.5 g). S5 exhibited the most expansive growth, characterised by dense fine and thick root formation, especially when compared to S30, which was located at the end of the irrigation pipeline. Other samples displayed similar sizes and root densities, reflecting the influence of plant position within the fertigation system. These results indicate that plants closer to the main irrigation pipe received higher water pressure and more consistent flow, leading to improved nutrient delivery (Díaz-Pérez & Eaton, 2015). Variations in root biomass may also be attributed to individual plant health, growth conditions, and nutrient uptake efficiency.

Furthermore, the IoT-based smart irrigation system optimised the growth cycle, reducing the time to harvest to 63 days, compared to 90 days under conventional fertigation. Similar observations were reported by Aurasopon et al. (2024), where lettuce grown in a hydroponic system using a semi-automatic IoT system showed enhanced growth and increased yield. This demonstrates the capacity of IoT-driven irrigation to accelerate crop development and improve production efficiency.

Conclusion

The analysis demonstrates that the implementation of an IoT-based irrigation system has a positive impact on growers. In terms of monitoring, IoT-derived data provided reliable and consistent measurements throughout the plant cycles, outperforming traditional manual assessments of the planting area. Plant growth parameters showed significant improvement, resulting in shorter cultivation periods compared to conventional fertigation practices. Consequently, these findings confirm that the IoT-based system is both effective and efficient in regulating irrigation, while simultaneously reducing labour requirements and enhancing economic outcomes through a shortened crop growth cycle.

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