Journal of Experimental Biology and Agricultural Sciences, October - 2023; Volume – 11(5) page 845 – 853

Journal of Experimental Biology and Agricultural Sciences

http://www.jebas.org

ISSN No. 2320 – 8694

Efficient Solar-Powered IoT Drip Irrigation for Tomato Yield and Quality: An Evaluation of the Effects of Irrigation and Fertilizer Frequency

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Received – June 30, 2023; Revision – October 30, 2023; Accepted – November 18, 2023
Available Online – November 30, 2023

DOI: http://dx.doi.org/10.18006/2023.11(5).845.853

KEYWORDS

Drip irrigation system

Fertilization

Time based irrigation

IoT

Tomato yield

ABSTRACT

The optimal management of irrigation and fertilization is crucial for maximizing the yield and quality of tomatoes grown in greenhouses. To address this challenge, this study aimed to develop and implement a solar-powered Internet of Things (IoT) based drip irrigation system for tomato cultivation in plastic roof net houses. Additionally, the study evaluated the effects of water and fertilizer frequency on tomato yield and quality. The experiment was designed with 2 irrigation frequencies (1 time in a day and 1 time in 2 days) and 3 fertilizer frequencies (1 time in 2, 4, and 6 days), with 4 replicates of the tomato variety CH154. The results showed that the solar-powered IoT-based drip irrigation system was efficient, precise in water and fertilizer control, and inexpensive to install and maintain. This allows for real-time monitoring of water flow rate, flow sensor status, treatment status, and electrical parameters on the Node-Red dashboard. Irrigation frequency had a significant impact ($p < 0.05$) on fruit number, weight, and length per plant, with 1-day irrigation resulting in a higher yield than 2-day irrigation. No significant interaction effect was found between irrigation and fertilizer frequency on tomato yield or quality. In conclusion, the solar-powered IoT-based drip irrigation system demonstrated precise control over water and fertilizer, proving its efficiency and cost-effectiveness. Real-time monitoring capabilities and the observed impact of irrigation frequency underscore its potential for enhancing tomato cultivation in greenhouses, offering a valuable contribution to sustainable and technology-driven agricultural practices.

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Peer review under responsibility of Journal of Experimental Biology and Agricultural Sciences.

Production and Hosting by Horizon Publisher India [HPI] (http://www.horizonpublisherindia.in/).

1 Introduction

Tomato (*Solanum lycopersicum L.*) is one of the most essential vegetables in the human diet due to its specific nutritional value, such as lycopene, phenolics, and vitamin C, and is the world's third-largest vegetable crop after potato and sweet potato (Mohammad et al. 2013). Tomato plants flourish on well-drained, fertile, slightly acidic loam soils with a pH range of 6.2 to 6.8. The tomato plant will not grow well in very acidic soils (pH less than 5.6), alkaline (pH greater than 7.5), or insufficiently supplied (Jones 2008). Furthermore, tomato plants are susceptible to many diseases and pests, and the available water and nutrients directly affect how well they grow (Salokhe et al. 2005).

Most farmers are encouraged to grow tomatoes in greenhouses instead of open fields when cultivating tomatoes. This is because greenhouse tomatoes are better in fruit size, TSS content, ascorbic acid, and acid content than open-field tomatoes (Juárez-Maldonado et al. 2014). Producing crops in a greenhouse offers several advantages, including i) Crops do not need chemicals, ii) Greenhouses provide an excellent environment for growing crops, iii) Greenhouses help avoid damage from getting rid of pests like weeds, insects, plant diseases, and so on (Salokhe et al. 2005). In addition, the most important benefit of farming in greenhouses is that it is possible to keep production up all year.

Drip irrigation in greenhouse farming is one of the solutions to environmental and resource issues that provides the best yield and highest quality products for agricultural crops. This is accomplished using minimal water inputs and high fertilizer efficiency (Salokhe et al. 2005). This technique provides an efficient irrigation system by giving plants the appropriate nutrients to minimize nutrient leaching (Elasbah et al. 2019). Some studies state that applying the appropriate amount of water is essential to improve water usage efficiency and production. Inadequate irrigation frequency, on the other hand, can result in a crop water deficit and a decrease in yield due to a lack of water and nutrients (Nut et al. 2019; Wang and Xing 2017).

As previously stated, a lack of suitable irrigation and fertilization frequency on tomatoes is one of the challenges to achieving both a maximum yield and a high quality. It can be seen that smart irrigation systems have significantly advanced, and it could be applied to such a system with precise irrigation and fertilization rates to analyze the effect of the amount of irrigation in combination with the fertilizer supply. Consequently, this study aims to develop and implement a solar-powered drip irrigation system that works with the Internet of Things to grow tomatoes in plastic roof net houses and to evaluate the effects of water and fertilizer frequency on tomato yield and quality.

According to the available research, there has been a lot of technological development to support drip irrigation. Smart irrigation systems mostly use solar power and IoT technologies to minimize water usage and energy costs. In the case of the smart irrigation system, which is powered by solar energy, demand-side energy management is a crucial method for avoiding serious supply shortages and improving energy efficiency. Before they are built and put in place, solar cell systems must be evaluated to see if the electricity made by each solar cell is enough to power the whole system during the day and if the electricity can be stored in an electric battery. Off-grid solar systems are often utilized for smart irrigation, and they may be found in areas with no electricity or where there is limited available energy (Madeti and Singh 2017; Rahman et al. 2018; Bouzguenda et al. 2019).

Aside from the use of solar energy, Internet of Things (IoT) technology has recently become widely used in the smart irrigation system. IoT-based smart irrigation systems have become increasingly common and competitive because they may result in more efficient and optimum water usage and significant waste reduction. Several innovations in the automated irrigation system have been proposed, with micro-processor devices to collect data from sensing systems. These are Arduino (Bouzguenda et al. 2019; Mahfuz and Al-Mayeed 2020; Pawar and Vittal 2019), Node MCU (Nawandar and Satpute 2019; Liwal et al. 2020), Raspberry Pi, wireless sensor network (WSN), and so on (Deveci et al. 2015; Al-Ali et al. 2019). Many additional developed models have been realized using low-cost sensors and actuators and communicating through GSM, Bluetooth, and LoRa (Kabalci et al. 2016; Stark et al. 2020). Some studies are conducted remotely through the Internet and utilize web-based or mobile applications to monitor data in real-time (Joy and Manivannan 2016; Wu and Lin 2019; Nițulescu and Korodi 2020).

2 Material and Methods

2.1 Power system design

The system architecture is designed for a solar-powered drip irrigation system based on the Internet of Things, as shown in Figure 1. The primary elements that make up the system under consideration are as follows:

2.1.1 Solar power system

The solar power system is composed of several components such as photovoltaic modules that convert solar energy to electricity and supply power to the water pump; electrical batteries that store the electricity generated by the PV modules and supply it to the water pump at the rate required for irrigation; a charge controller or charge regulator that regulates the rate at which electric current is applied or drawn from the electrical batteries; and an inverter for DC/AC conversion.

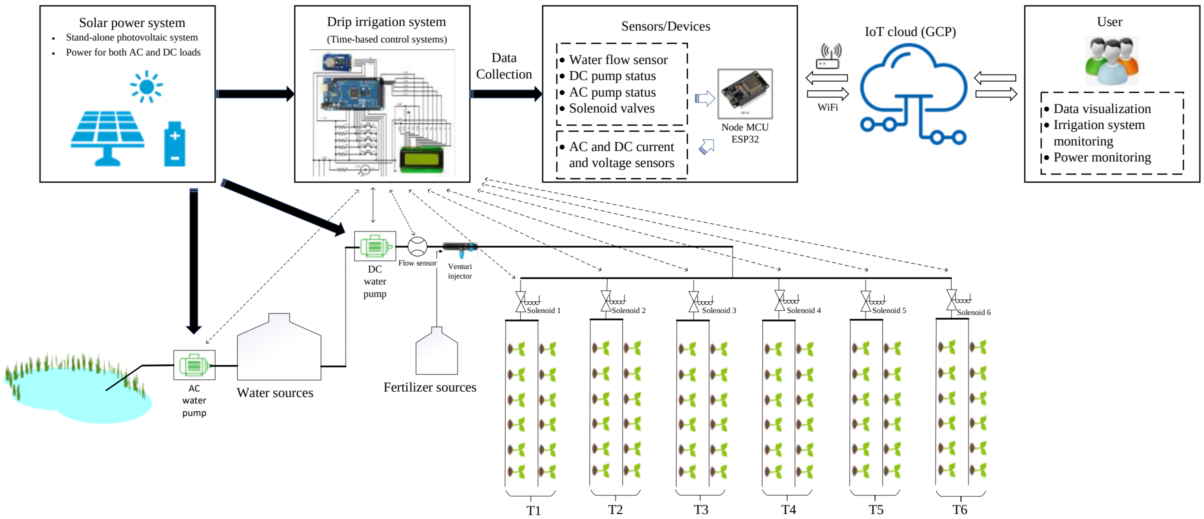


Figure 1 Overall system architecture

2.1.2 Energy requirement assessment

When using solar cells in stand-alone systems, the size of the solar panel, battery, charger, and inverter must be calculated to meet the requirements of electrical appliances such as water pumps and light bulbs. Calculating the energy demand is the most important task for optimal irrigation, as it considers the electricity source, working power, time for each item, and daily energy usage for each component. The energy demand for the solar PV system is presented in Table 1. The table in the bottom row presents the corrected daily capacity, with a correction factor of 25 percent.

2.1.3 Battery selection

To calculate the capacity of a 12V battery needed to supply 133.75 watts of power, we can use the following formula (Bouzguenda et al. 2019)

$$\text{Battery capacity} = \frac{\text{Daily Energy}}{\text{Battery Voltage}} \quad (1)$$

However, there are 20% energy losses while charging and discharging, and the estimated battery size is 13.94 Ah. In addition, the battery must have a minimum discharge depth for better operational life (DOD). In this analysis, a DOD of 50% is assumed, and as seen in the following equation, the battery capacity is thus at least 27.88 Ah. Therefore, the most suitable battery current on the market is 30 Ah (Bouzguenda et al. 2019).

$$\text{Size of solar panel} = \frac{\text{Total battery capacity}}{\text{Charging time}} \quad (2)$$

2.1.4 Size of the solar panel

During the day, the battery can be entirely charged by solar panels. The peak sunlight in Thailand remains 4.54 hours a day. The size of a solar panel is determined by the total battery capacity divided by the charging time (equation 2). So, the size of the solar panel calculation is 36.85 W. This analysis's main power source was a 40 W polycrystalline solar panel.

2.2 IoT design system

2.2.1 IoT-based drip irrigation system

The architecture will provide time-based control systems to manage and control the drip irrigation system. The operation utilizes a processing board, the Arduino Mega 2560, and the DS1307 serial real-time clock (RTC) for timekeeping. At program start-up, the software will read the configuration value from the SD card, which will keep the default settings of time and water requirements in each tomato growth phase. This was performed by

Table 1 Daily irrigation system energy required

Device	Number of items	Voltage (V)	Current (mA)	Power (mW)	Operating time (hour)	Energy (Wh)
DC water pump	1	12	6,000	72,000	1	72
AC water pump	1	220	160	35,000	1	35
Daily energy (Wh)			107			
Adjusted daily energy (Wh)			133.75			

comparing the scheduling time and RTC to control relays for switching the DC water pump. The pump's control is managed by using a water flow sensor to obtain the desired quantity of water. The amount of water and fertilizer applied to each tomato treatment was managed by solenoid valves attached to the different treatments. During drip irrigation, the data from various sensors and devices, including water flow, DC and AC pump status, and solenoid valve status, is transmitted to the Node MCU ESP32 to be collected before being transmitted to the IoT cloud. This board was chosen because it is a low-energy consumption microcontroller with built-in Wi-Fi, dual-mode Bluetooth and low power consumption.

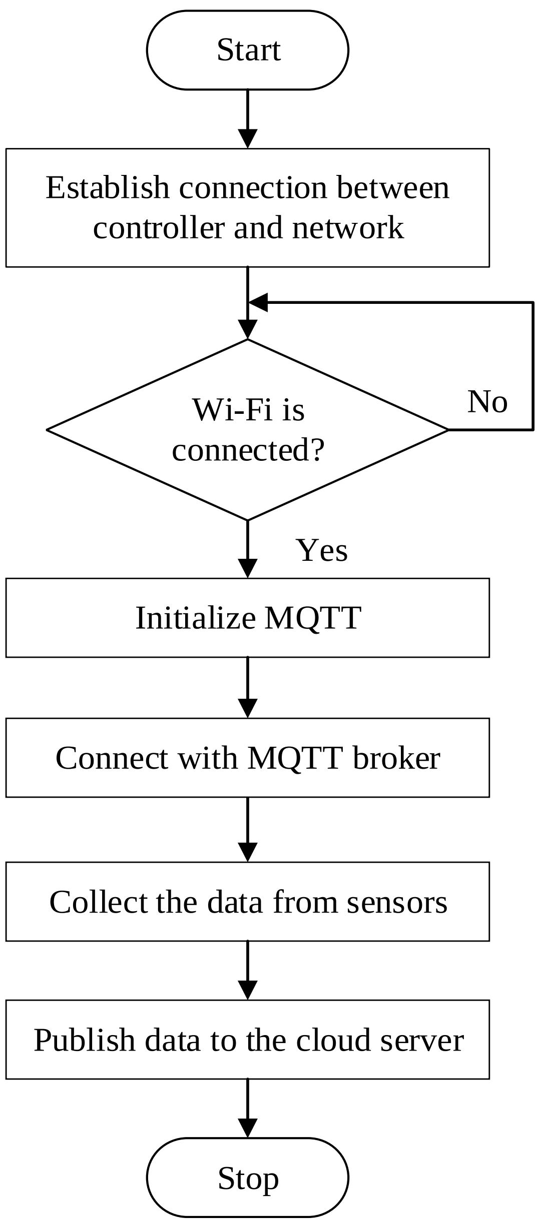


Figure 2 ESP32 programming flowchart

To monitor the electrical power usage, ESP32 is determined to be the system's micro-controller, collecting and processing data from current and voltage sensors and transmitting processed data to the cloud and servers via the Wi-Fi network. The application involves two mean sensors that sense four physical signals: AC current and voltage sensors (PZEM-004) and DC current and voltage sensors (PZEM-016). This smart energy sensor senses current and voltage, which provides overall energy consumption and reads in digital form. AC Digital power meter module PZEM-004T can handle voltage readings of up to 260 VAC and power up to 100A, despite power output at 3.3 or 5 volts. DC digital power meters and USB to 485 are available with PZEM-017 for high-sided electricity up to 300 volts and up to 300 A, with power 3.3 or 5 V. ESP32 is used to process electrical voltage and current values in real time to create DC and AC node sensors.

As part of communication between the data from sensors/devices and cloud service applications, the ESP32 collects and communicates real-time data via a Wi-Fi network. The collected data can be transferred to the cloud server via the Message Queuing Telemetry Transport (MQTT) protocol, an energy-efficient protocol that uses a low-energy application layer. Figure 2 shows the ESP32 programming flowchart as given below.

- Initialize the system and connect the controller and network via Wi-Fi Access Point.
- Check for the connectivity of Wi-Fi. If so, go to the next level. Alternatively, maintain the Wi-Fi link.
- Initialize the MQTT, connect to the broker, and subscribe to the topic.
- Collect the data from the measurement sensor.
- Publish the data to the cloud server.

2.2.2 Google Cloud Platform

The monitoring system used the Google Cloud Platform (GCP) to view the real-time sensor values. The core capability of Google Compute Engine is to create an instant and install Ubuntu 16.04 LTS operating system on this virtual machine. MQTT protocols, Node-RED, InfluxDB, and Grafana, are implemented for monitoring in the server section of the solution, as shown in Figure 3. The MQTT broker (Mosquito) serves as the main centre location in this application, and all data is sent to the broker through publish-subscribe communication.

2.3 Experimental setup

The experiment was conducted at the Creating Innovation for Sustainable Development Research Centre (CISD-RC), Nakhorn Pathom Rajabhat University, Thailand (Latitude: 13°51'41.6" N;

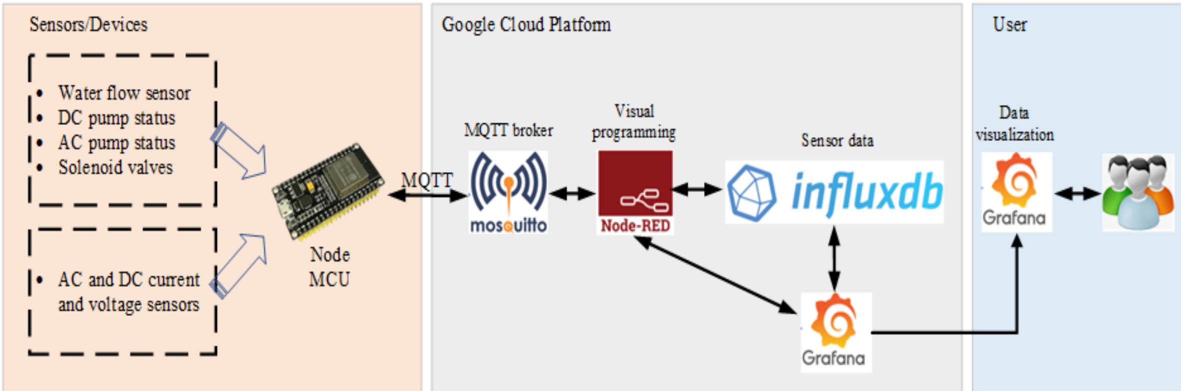
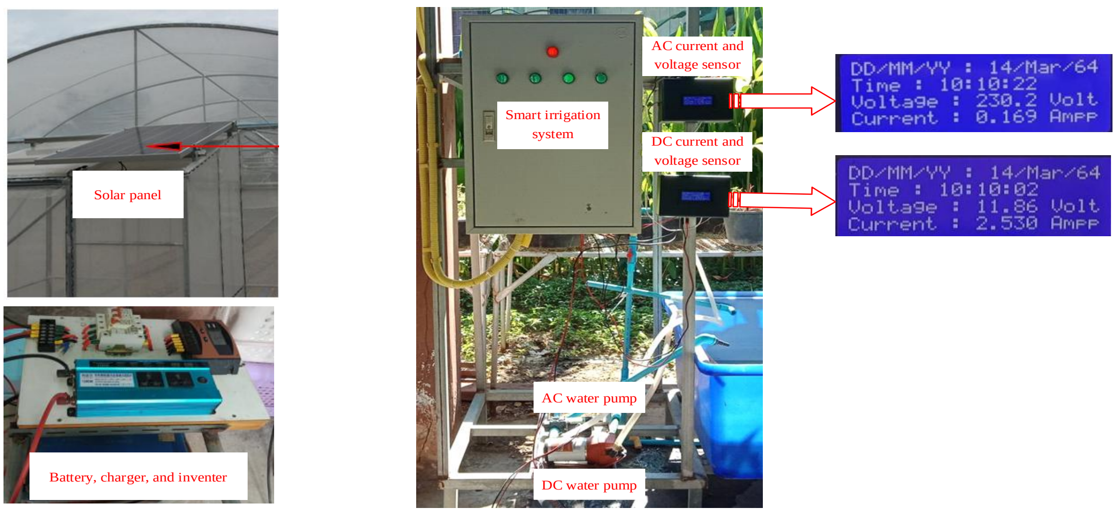


Figure 3 Monitoring system



(a) (b)

Figure 4 (a) Solar power system and (b) Smart drip irrigation system

Longitude: 99°59'49.6"E) during the growing season of 2019 and 2020. The tested variety was "CH154", developed from cherry tomatoes with a small fruit size, not more than 15 grams, and a sweet flavour. It is ready to harvest 70-75 days after germination.

The factorial experiments on tomato production were designed as 2x3 with 4 replicates in Completely Randomized Design (CRD) to evaluate the effects of irrigation and fertilizer frequency of cherry tomatoes (CH154 variety). Treatments consisted of two irrigation frequencies (1 time in 1 and 2 days) and three fertilizer frequencies (1 time in 2, 4, and 6 days)

We put seeds from the CH154 variety in seed-starting trays to grow cherry tomatoes. Plantain seedlings grow on coconut husks. Daily deep watering is recommended. After the seedlings had developed for 30 days, 576 seedlings were transplanted to each plot. The trees were planted in a greenhouse in a 12-inch round pot using planting material made up of a mixture of coconut husks and chopped coconut husks in a ratio of 1:1.

Experimental models on water consumption were applied based on Penman-Monteith models to evaluate the water requirements in each tomato growth phase: Initial, development, middle, and late stage. Salokhe et al. (2005) examined how much water a drip irrigation system needs in tropical areas. Regarding fertilization, the Jensen and Malter (1995) formula is used; it is a popular formula for growing tomatoes with high growth and yield (Jensen and Malter 1995).

Although a greenhouse with a permanent structure provides a chance to achieve maximum output and high-quality tomatoes, the cost of producing tomatoes in greenhouses is higher. Therefore, to reduce the construction expense, this research utilized a simple net house with a plastic roof for the field experiment. In a system implementation, a prototype of drip irrigation systems was assembled in a control cabinet and installed in the plastic roof net-house condition size of 12x20 m, as shown in Figure 4. The drip irrigation system was set up with high-pressure micro diaphragm water pumps. This pump used water and fertilizer from the water and fertilizer tank to get to the field, and solenoid valves controlled it. Each treatment was separated into two rows utilizing 20 mm low-density polyethylene pipe (LDPE). Each row comprises 12 inches of round pots on both sides of the pipe. Set a distance of 40 cm between the pots, which can accommodate 48 pots per side, totalling 96 per row on both sides. Use a 3 mm drip pin to connect to a micro-PVC (MT/PVC) pipe to deliver water to each pot. The control system consists of a 1000-liter water tank and a 200-liter fertilizer tank connected to an AC 220 V pump that pumps water into the water tank. The system utilizes a DC 12V diaphragm pump with a flow rate of 7 liters/min for irrigation and a water flow sensor with a working range of 1–30 liters to monitor and control the amount of water and fertilizer for each treatment.

2.4 Statistical analysis

In data collection, weekly trends in vegetative development parameters were identified, and plant samples were collected using a CRD design to determine the crop yield and quality of tomatoes under different treatments. The statistical analysis was processed by one-way analysis of variance (ANOVA) using the SPSS computer software package to estimate the main effects of different sources of variation and their interactions. Treatment means were compared at a 5% level of probability using the least significant difference (LSD) method.

3 Results

3.1 Data collecting for solar-powered IoT-based Drip Irrigation System

To verify the accuracy of voltage and current sensors, the experiment was carried out at Nakhorn Pathom Rajabhat University, Thailand (Latitude: 13°51'41.6" N; Longitude: 99°59'49.6"E) during December 11–12, 2020. The sensors detected four physical signals and were compared to traditional measuring equipment, including AC voltage and current sensors and DC voltage and current sensors. The results are summarized in Table 2. AC voltage and current sensors showed errors of 0.130 and 0.101 percent, respectively, while DC voltage and current sensors had errors of 0.297 and 5.173 percent.

To monitor the drip irrigation system, collected data, which includes the water flow rate of DC and AC pumps, flow sensor status, and treatment status, is transmitted to the IoT cloud and shown in real-time on the Node-RED dashboard (Figure 5)

Table 2 AC and DC voltage and current percent error

Experiment and trial		AC voltage		AC current		DC voltage		DC current	
Date	Time	Measured (V)	Standar (V)	Measured (A)	Standard (V)	Measured (V)	Standard (V)	Measured (A)	Standard (A)
12/11/2020	10:30 am	229.10	229.10	229.30	0.74	11.75	11.80	3.93	3.71
12/11/2020	04:30 pm	228.50	228.50	228.90	0.74	11.71	11.74	3.79	3.60
12/12/2020	10:30 am	229.20	229.20	229.50	0.74	11.73	11.76	3.82	3.68
12/12/2020	04:30 pm	229.10	229.10	229.40	0.74	11.75	11.78	3.91	3.70
Mean		228.98	229.28	228.98	229.28	11.74	11.77	3.86	3.67
% Error		0.130		0.101		0.297		5.173	

Figure 5 Caption of drip irrigation monitoring system

Table 3 Effect of irrigation, fertilization, and their interaction on tomato yield and quality

Treatments	Number of fruit/plant (number)	Fruit weight/plant(g)	Fruit weight (g)	Fruit width (mm)	Fruit length (mm)	TSS (ºBrixs)
Irrigation (days)						
1 (I_1)	295.83[a]	2333[a]	9.38[a]	.2120[a]	34.11[a]	8.66[a]
2 (I_2)	270.33[b]	1833[b]	8.67[b]	.2152[a]	31.37[b]	8.30[a]
F–test	6.33	8.44	5.62	1.73	10.33	2.26
p-value	0.02*	0.011*	0.03*	0.20	0.01**	0.15
Fertilizer (days)						
2 (F_2)	273.16[b]	1875[b]	9.56[a]	21.29[a]	33.24[a]	8.83[a]
4 (F_4)	286.22[a]	2125[ab]	8.66[b]	21.03[a]	32.86[a]	8.40[a]
6 (F_6)	289.88[a]	2250[a]	8.84[ab]	21.76[a]	32.13[a]	8.22[a]
F–test	1.00	1.64	3.42	3.07	0.58	2.30
p-value	0.39	0.23	0.06	0.08	0.57	0.13
Irrigation*Fertilizer						
I_1F_2	270.81[b]	2000[ab]	10.31[a]	21.10[ab]	34.85[ab]	9.14[a]
I_1F_4	298.94[ab]	2500[a]	8.94[b]	20.97[b]	35.22[a]	8.60[ab]
I_1F_6	317.75[a]	2500[a]	8.88[b]	21.54[ab]	32.28[b]	8.26[ab]
I_2F_2	275.50[b]	1750[b]	8.81[b]	21.49[ab]	31.63[c]	8.53[ab]
I_2F_4	273.50[b]	1750[b]	8.38[b]	21.10[ab]	30.51[c]	8.20[b]
I_2F_6	262.00[b]	2000[ab]	8.81[b]	21.98[a]	31.99[bc]	8.18[b]
LSD ($p<0.05$)	NS	NS	NS	NS	NS	NS

3.2 Effects of irrigation and fertilizer frequency on tomato yield and quality

The results of the effects of irrigation and fertilizer frequency on cherry tomatoes (CH154 variety) are given in Table 3. The findings indicate that irrigation frequencies (1 time in 1 and 2 days) and three fertilizer frequencies (1 time in 2, 4, and 6 days) did not affect tomato yield and quality. Under the "Irrigation (days)" section in Table 3, the p-values for the F-test are provided. The p-values for the parameters like "Number of fruit/plant," "Fruit weight/plant," and others are less than 0.05, indicating statistical significance. On the other hand, under the "Fertilizer (days)" section, the p-values for F-test are often higher than 0.05, suggesting that the fertilizer frequencies did not significantly impact these parameters. So, while tomato yield and quality are discussed collectively, the document highlights that the irrigation frequencies significantly influenced these factors, whereas the fertilizer frequencies did not show a significant effect based on the statistical analysis. However, when looking at the detailed experimental results in Table 3, it becomes apparent that while irrigation frequencies did show significance for certain parameters (number of fruits per plant, fruit weight per plant, fruit weight, and fruit length), the fertilizer frequencies did not have a significant effect on yield or quality.

4 Discussions

The advancements in drip irrigation technology are highlighted, focusing on integrating solar energy and IoT technology. Solar-powered smart irrigation systems' effectiveness and energy efficiency are evaluated, especially for off-grid areas. IoT in smart irrigation systems has become widespread due to its ability to optimize water usage and reduce waste. Adopting drip irrigation in greenhouses is promoted for efficient water and fertilizer usage, leading to higher crop yields and better quality. Integrating solar energy and IoT technology in smart irrigation systems is also emphasized to enhance efficiency and reduce waste.

An experiment was conducted to evaluate the effects of irrigation and fertilizer frequency on the yield and quality of cherry tomatoes (CH154 variety) grown in plastic roof net-houses greenhouses. The experiment used a 2x3 factorial design with 4 replicates and was conducted in a CRD design. The results showed that the frequency of irrigation (1 time in 1 day and 2 days) significantly affected the number of fruits per plant, fruit weight per plant, fruit weight, and fruit length. Among the tested treatments, the 1-day irrigation treatment gave a higher yield and quality than the 2-day irrigation. However, the frequency of fertilizer (1 time in 2, 4, and 6 days) did not significantly affect yield or quality. The findings of this research were in agreement with those obtained by Wang and Xing (2017), who discovered that irrigation was more sensitive to fruit yield than fertilization. Besides, in a study concerning the cultivation of melons, Sensoy et al. (2007) found that the treatment that provided the highest irrigation compensation resulted in the highest melon yield (Sensoy et al. 2007). Further studies can be conducted to optimize the system and evaluate its impact on other crops and in different growing conditions (He et al. 2021; Zhang et al. 2022; Zhu et al. 2022). The study provides a foundation for future work in developing sustainable and efficient agricultural technologies.

Conclusions

The results of this study were as follows: (i) Solar-powered IoT-based drip irrigation systems can work with a precise irrigation time. All collected data, which includes the water flow rate of DC and AC pumps, flow sensor status, treatment status, and electrical parameters, can be shown in real-time on the Node-Red dashboard. It was recommended that the system was relatively inexpensive to install and maintain precise in its control of the water and fertilizer to the greenhouse tomato, (ii) For the effects of irrigation and fertilizer frequency on the CH154 variety of cherry tomato, both irrigation frequencies (1 time in 1 and 2 days) and three fertilizer frequencies (1 time in 2, 4, and 6 days) had no interaction effect on tomato yield and quality. The irrigation frequencies are significantly different ($p < 0.05$) for number of fruits per plant, fruit weight per plant, fruit weight, and fruit length. The frequency of 1-day irrigation gave a higher yield (number of fruits/plant and fruit weight/plant) than 2-day irrigation treatment.

Acknowledgement

This Research was Financially Supported by the Faculty of Engineering, Mahasarakham University (Grant year 2021).

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