International Journal of Environmental Science and Technology (2020) 17:3901–3916
https://doi.org/10.1007/s13762-020-02737-6

ORIGINAL PAPER

Portable, wireless, and effective internet of things-based sensors for precision agriculture

K. R. Gsangaya[1] · S. S. H. Hajjaj[2] · M. T. H. Sultan[3,4,5] · L. S. Hua[6]

Received: 20 January 2020 / Revised: 22 March 2020 / Accepted: 1 April 2020 / Published online: 16 April 2020

Abstract

Profitability in production farming depends on making correct and timely operational decisions based on current conditions and historical data. Precision agriculture is a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique conditions found in each field while maintaining environmental quality. This research paper details the development of a portable and wireless sensor network system to remotely monitor the environmental parameters in an agriculture field and provide field managers with alerts and information regarding current conditions while saving the data in a database for future reference. The data acquisition unit consisting of sensors and microcontroller captures the environmental parameter data such as temperature, humidity, light intensity, and soil moisture content. By utilizing Internet of Things technology, the information captured by the sensors is uploaded wirelessly to the cloud server and can be viewed by users from anywhere in the world via an Internet-enabled device. The rugged and water-resistant enclosure ensures that the system can be used in outdoor agriculture fields, while a solar power supply eliminates cabling needs and reduces maintenance of sensor nodes. Tests conducted on the system show that it can successfully capture and display environmental parameter data to users.

Keywords Precision agriculture · Internet of things · Wireless sensor network · Data acquisition

Editorial responsibility: Shahid Hussain.

✉ K. R. Gsangaya
kisheenrao@gmail.com

1 College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor Darul Ehsan, Malaysia

2 Centre for Advanced Mechatronics and Robotics (CaMaRo), Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor Darul Ehsan, Malaysia

3 Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor Darul Ehsan, Malaysia

4 Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor Darul Ehsan, Malaysia

5 Prime Minister's Department, Aerospace Malaysia Innovation Centre (944741-A), MIGHT Partnership Hub, Jalan Impact, 63000 Cyberjaya, Selangor Darul Ehsan, Malaysia

6 Laboratory of Biopolymer and Derivatives, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor Darul Ehsan, Malaysia

Introduction

All around the globe, humanity is preparing for a population explosion that will reach a total of 10 billion people in 2050 (United Nations 2017). It has been estimated that global food production must increase by at least 70% over the coming years to keep pace with this growth (Thornton et al. 2018; Sonnino et al. 2019; Dinar et al. 2019; Silvade et al. 2019). Farming practices have not changed much over the years, and farmers still use traditional approaches based on assumptions of the nutritional needs of the crop. Supplying the same input of nutrients across the entire farm is no longer the best option, as this leads to heavy use of fertilizers and pesticides, excessive water consumption, environmental degradation, and high operating costs (Adila and Bahaman 2013; Blandford et al. 2014; Erbaugh et al. 2019).

To help reverse this trend and generate enough food to meet the growing demands, the agriculture industry needs to embrace smarter farming methods. Innovative agricultural techniques such as precision agriculture methods can help alleviate some of these concerns. Precision agriculture is an approach to farm management that uses information technology to distribute the resources efficiently and ensure that the crops and soil receive the exact nutrients required at the right time for optimum health and productivity (Ullah et al. 2017).

In recent years, researchers have attempted to develop agriculture monitoring systems that capture environment and crop data from the agriculture field by utilizing cloud computing and the internet of things (IoT) technology. IoT can be defined as a network of physical objects that connect and exchange data wirelessly over the Internet (Deshpande et al. 2017). Using this data, field managers can direct resources, including material, equipment, and workforce, to where they are needed the most, resulting in efficient agricultural operations, reduced costs, and increased profits (Kamilaris et al. 2016; Khanna and Kaur 2019).

However, previous iterations of agriculture monitoring systems have been plagued with issues that have hindered the growth of this sector. Early agriculture monitoring systems consisted of wired data acquisition systems, in which the sensor units were connected by a wired connection to the monitoring center. Such systems have numerous limitations, such as a limited size of deployment for monitoring points due to the wiring connection range; high installation, maintenance, and relocation costs due to extensive cabling; and cables that are easily damaged if placed outdoors under harsh conditions (Zhang et al. 2002; Pallavi and Mallapur 2017; Ramya et al. 2017). These data acquisition units are also designed to be used under controlled environments such as greenhouses or food factories and lack the ruggedness to be used outdoors for extended periods (Dwarkani and Ganesh 2001; Palowski et al. 2009; Pradeep and Byregowda 2017).

Recent advancements in wireless sensor network (WSN) technology have been able to overcome certain issues related to the wired sensor systems (Patil and Kale 2016; Prathibha and Jyothi 2017; Ma and Chen 2018). WSNs can operate in a wide range of environments and provide advantages in terms of cost, size, power consumption, flexibility, and distributed intelligence. In a network, when a node cannot directly contact the base station, the message may be forwarded over multiple hops. By auto-configuration setup, the network could continue to operate as nodes are moved, introduced, or removed (Xuemei et al. 2008; Krishna et al. 2017).

WSNs can be classified based on their communication protocols. Earlier versions of wireless networks used radio frequency (RF) technology and Bluetooth. Examples of systems using RF modules include a sensing system based on a feedback control mechanism which regulates the flow of water on to a field in real time based on instantaneous temperature and moisture values. The sensor data is transmitted via a 433 MHz RF module and collected in a central processing unit (Nandurkar et al. 2014). Next, an automated irrigation system developed and experimented with dwarf cherry trees utilizes Bluetooth technology to enable a low-cost wireless-controlled irrigation solution and real-time monitoring of water content of soil. Data acquisition is performed by using solar-powered wireless acquisition stations for the purpose of control of valves for irrigation (Dursun and Ozden 2011).

RF and Bluetooth communications were replaced by ZigBee and wireless local area network (WLAN) technologies based on low-cost, low-power, and adequate data rate requirements. Agricultural monitoring systems utilizing ZigBee technology include a drip irrigation system with fuzzy control, which measures four parameters, soil moisture, temperature, light intensity, and electrical conductivity, for drip irrigation decision making (Xiang 2011). As for WLAN- or Wi-Fi-based systems, one system uses motion detectors placed around an agriculture field to sense any unusual movements from animals which may destroy the crops in the field. This information is transmitted over the Wi-Fi network to a server, which processes the information and switches on an alarm to scare away pests, animals, and intruders (Dagar et al. 2018).

Some wireless network systems have duplex communication link based on a cellular/Internet interface that allows for data transmission in the event that one communication protocol fails (Sushanth and Sujatha 2018). However, these WSN systems have an added issue of limited transmission range and high infrastructure costs (Kalaivani et al. 2011; Mathurkar and Chaudari 2013).

A new and exciting long-range wireless communication protocol, LoRaWAN, has been steadily gaining traction in the wireless network community as of late. LoRa network was specifically designed for IoT applications with the purpose of connecting thousands of sensors, modules, and appliances over a large network. LoRa can achieve data transmission range of 2–5 km in urban areas and up to 15 km in suburban areas. The network requires minimal maintenance with low power consumption which makes it ideal for large number of sensors. LoRa can be used in applications where there is no external power supply, such as in agriculture fields, as LoRa applications can run on battery power supply for years. One disadvantage of LoRa network is its low data rates which prevents this protocol to be used in real-time and high-throughput applications such as VoIP and video transmission (Adelantado et al. 2017).

An agricultural monitoring system based on LoRa network for long-range and low-power consumption data transmission from the sensor nodes to the cloud services was developed. This system of cloud services is highly scalable and utilizes multiple data streams for analytics purposes. The system was tested in a vineyard field to collect air temperature and humidity, as well as leaf wetness and soil moisture readings. The prototype consists of three collector nodes and one executor nodes which are positioned in 1 km radius from the base station. Based on the soil moisture and leaf wetness measurements, the data analytics service makes a decision if the irrigation system needs to be turned on or off (Davcev et al. 2018).

WSNs can be further categorized based on the types of power supply. Many wireless systems still rely on external power supply via cables; thus, defeating the purpose of having wireless data transmission capability (Rehman et al. 2011; Roselin and Jawahar 2017; Kavitha et al. 2018). Some fully wireless data acquisition units use rechargeable batteries capable of powering the devices for several months, though these systems require extensive maintenance to charge or replace the batteries (Kumar and Kumar 2015; John 2016; Mat et al. 2015).

Thus, there exists a need for a simple, low-cost, wireless precision agriculture monitoring system that is highly portable and rugged for outdoor use, self-powered to reduce the need for extensive power supply cabling, while providing added functionality that not only reduces agriculture workload but also increases crop yield and profits.

This research work aims to develop an improved system to monitor the environmental parameters in an agriculture field remotely and provide field managers with alerts and information on current conditions while saving the data in a database for future reference. The rest of this paper is organized as follows. "Development of the data acquisition system" section describes the development of the portable and wireless monitoring system for agriculture fields in greater detail, followed by testing and analysis of the system in "Performance analysis" section. Finally, the paper concludes with a summary of this work and future plans in "conclusion" section.

This research work was carried out from June 2018 to March 2019 at Universiti Tenaga Nasional, Putrajaya Campus and the Malaysian Agricultural Research and Development Institute, Serdang. This research work has also resulted in the filing of a patent with the Intellectual Property Corporation of Malaysia (MyIPO), with filing number, UI2019005917 (Hajjaj and Rao 2019).

Materials and methods

Description of the data acquisition system

The data acquisition system includes the means to accurately determine the ambient conditions at an agriculture field. For this research work, a total of three sensors, which include, an air temperature and humidity sensor, a light intensity sensor, and a soil moisture sensor, were utilized to capture four environmental parameters, namely temperature, humidity, surrounding light intensity, as well as soil moisture content.

Furthermore, the flexibility of the system allows additional sensors to be included in the system based on user requirements. These include a pH sensor to determine soil acidity; UV sensor to determine ultraviolet light intensity; carbon dioxide and oxygen sensors to monitor the surrounding air composition; rain sensor to detect rainy weather; and an ultrasonic sensor to detect flooding in the field. Using ultrasonic sensors, water height can be determined, based on a pre-defined acceptable level. The sensor shoots a short ultrasonic pulse at the surface of the water and then based on the time of its echo to return, as well as the speed of sound, the distance between the sensor and the surface of the water, or water height, can be measured (Hajjaj et al. 2020).

The microcontroller was used to read the environmental parameters captured by the sensors, process the data, and upload the data wirelessly over a communication network to the cloud server.

The microcontroller acts as a pathway for the transmission of data from the sensors to the cloud server through Message Queuing Telemetry Transport (MQTT) and JavaScript Object Notation (JSON) script. MQTT is a publish-subscribe-based messaging protocol designed for connection with remote locations where network bandwidth is limited. JSON is an open-standard file format that uses human-readable texts to transmit data objects consisting of attribute–value pairs and array data types. The environment and field data were transmitted to the cloud server via a gateway connected to wireless access points (WAP) located in the field, which form a wireless local area network (WLAN), as presented in Fig. 1. The number of WAPs used can vary

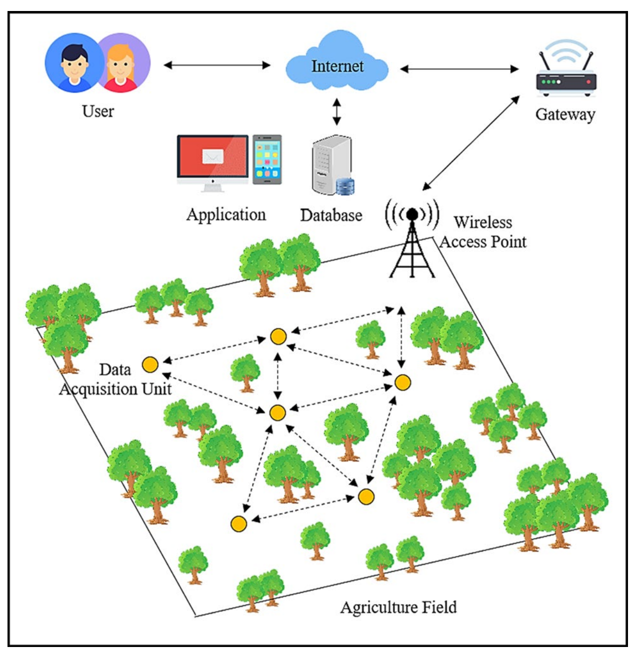


Fig. 1 WSN layout for agriculture fields

depending on the required wireless communication network range based on the size of the agriculture field and the number of data acquisition units deployed.

In large agriculture fields, certain environmental parameters can vary drastically from one corner of the farm to the other. For example, while one side of the field may have been irrigated adequately, the other side could be dry and not suitable for crop growth. Thus, to monitor the whole field, multiple data acquisition units are deployed across the entire field, forming a WSN as shown in Fig. 1, for accurate agriculture monitoring.

In the cloud server, live information from all agriculture fields was collected and stored, with regards to Fig. 2. The data stored in the cloud server can be accessed remotely by clients using either the browser on an Internet-enabled device to access the IoT platform webpage or a custom mobile application. This field information can then be utilized to assist field managers in directing the resources to where they are needed the most, resulting in efficient agricultural operations and reduced usage of resources, which leads to reduced environmental pollution, lower costs, and increased profits. Additionally, the field information can be used as input data to automate the irrigation systems in the field and control the greenhouse and food factory environments by automating the ventilation fans, humidifiers or dehumidifiers, and lights for optimum crop growth. Lastly, the information from the monitoring system can be used to control heavy agriculture machineries such as tractors and harvesters.

The agriculture monitoring system developed for this research work is cost-effective, multifunctional, and can be fitted to any agriculture field via the plug-and-play method. The system is also powered via solar energy, making individual data acquisition units fully wireless and portable, thus eliminating the need for an extensive cabling for power supply and data transmission, leading to reduced installation, maintenance, and relocation costs.

Development of the data acquisition system

Design requirements

For this research work, a novel and improved data acquisition unit for precision agriculture monitoring was developed. Several aspects were incorporated into the prototype of data acquisition unit for improved functionality. Firstly, the device was made to be water resistant so that it can be utilized for outdoor applications. Next, the device was designed to be rugged with the components fixed securely in place so that it will be able to survive heavy damage from drops, extreme weather conditions, and animal bites. Besides, the device will have to be self-powered, in this case via solar panels, so that it may be highly portable and fully wireless. Furthermore, the device should be able to function without jeopardizing the performance of the sensors. Lastly, the device must also be ergonomic so that it can be opened easily to replace the components inside the case while maintaining its robust functionality.

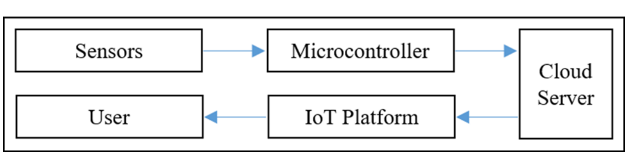


Fig. 2 Block diagram of agriculture monitoring system

Components of the data acquisition unit

The prototype data acquisition unit was assembled using off-the-shelf components to keep costs to a minimum. The microcontroller selected for this application was the Arduino Uno R3 board which consists of 14 digital pins along with 6 analogue pins. A wireless network module allows the microcontroller to transmit the data captured by the sensors wirelessly over the Internet to the cloud server. Since the Arduino Uno microcontroller is not a wireless network-ready board, an external ESP8266 Wi-Fi module was required for the system. The DHT22 digital temperature and humidity sensor was selected for the prototype model. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air and produces a digital signal on the data pin. A GL55 photoresistor was selected as the light intensity sensor. Since the resistance of a light-dependent resistor changes as the amount of light falling on it varies, by measuring the resistance of the photoresistor, the ambient light intensity can be determined as well. Similarly, an FC-28 soil moisture sensor which consists of two probes was used to measure the volumetric content of water in the soil based on the corresponding change in resistance.

The solar power supply was vital to ensure portability and a fully wireless system. A 12,000 mAh solar rechargeable power bank was selected as the power supply. During the day, the lithium polymer battery is charged via the built-in 1.2 W monocrystalline solar panel using solar energy. The connection of all the components is detailed in Fig. 3.

Assembly of the data acquisition unit

The first process in the development of the prototype of data acquisition system was to design the case to fit all the components of the system. The dimensions of the components were determined, and the corresponding case was designed using computer-aided design (CAD) software, CREO Parametric. The case comprises two portions: an upper part

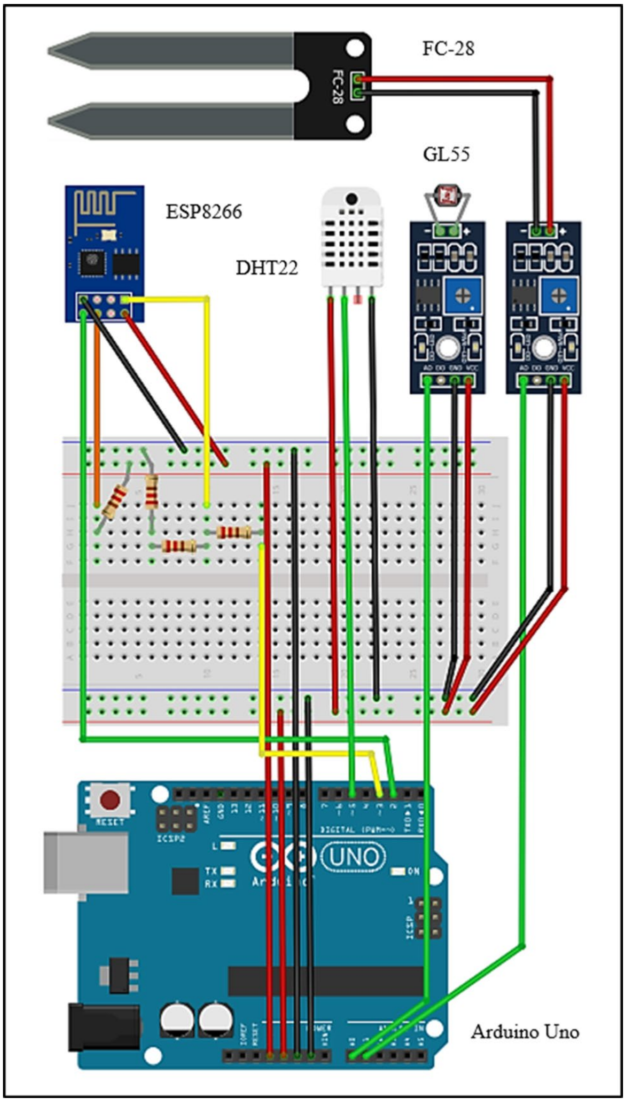


Fig. 3 Schematic diagram of the data acquisition unit

consisting of the solar power bank and light sensor placement and a lower part for fitting the rest of the components.

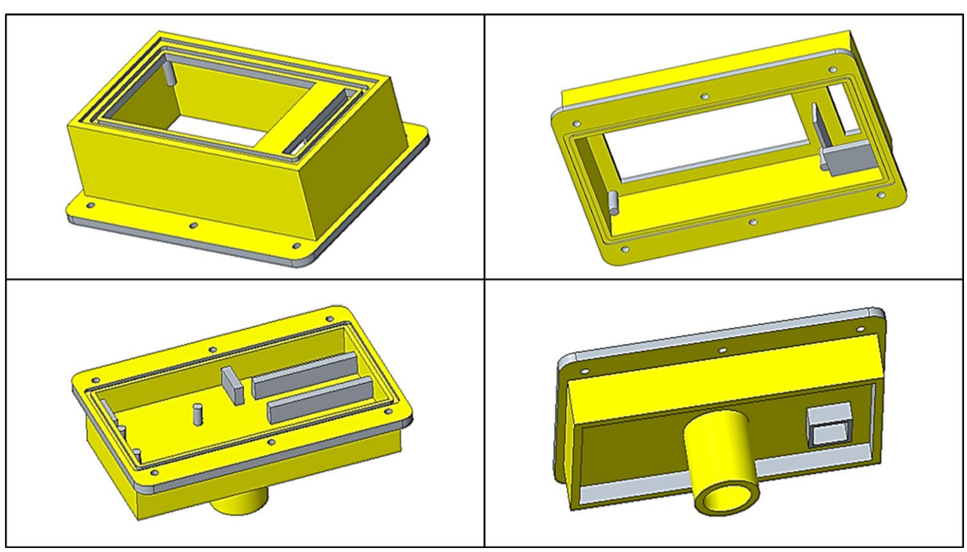
As shown in Fig. 4, the top part of the case includes a window to expose the solar power bank and light intensity sensor to sunlight. The window was covered by a clear acrylic panel attached to a rubber O-ring to ensure water resistance. For the bottom part, the case was partitioned with grooves so that the components can be secured in place with screws. The CAD model was then 3D-printed using polylactic acid (PLA) filament, which is a plant-based plastic that is extremely durable and waterproof. PLA material also enables the transmission of the wireless network signals to the wireless module in the data acquisition unit.

The components were then assembled into the case as presented in Fig. 5. The microcontroller was screwed into place, and the power and data pins on the sensors were connected to the corresponding pins on the board via jumper cables. The sensors were then screwed into place in the case. A small hole was drilled at the bottom part of the case to expose the DHT22 temperature and humidity sensor to the environment.

A skirt was designed at the bottom part to prevent water ingress through the hole from rain. The top and bottom parts were assembled together with screws and bolts along with another rubber O-ring to ensure water resistance. A pole was attached to the bottom part of the case for support and to ensure that the device is slightly raised off the ground to prevent water ingress into the device in the event of flooding. The pole also houses the power and data cables of the soil moisture sensor that need to be placed into the ground.

Next, the custom code required to capture the environmental data via sensors and to upload the information to the cloud server was developed using Arduino IDE programming interface and uploaded to the Arduino Uno microcontroller in the data acquisition unit. The sensor readings

Fig. 4 Case design for the data acquisition unit



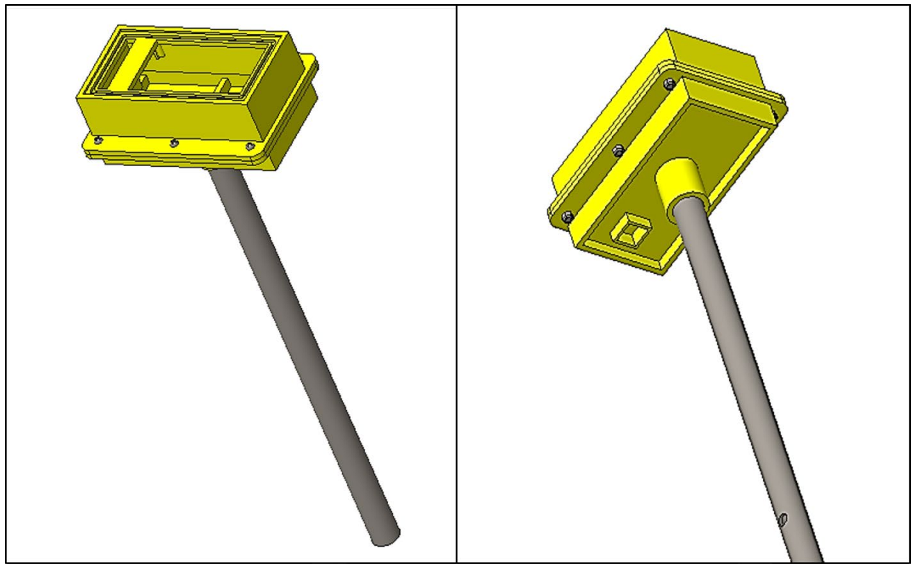


Fig. 5 CAD model of fully assembled system

were uploaded to ThingSpeak cloud server and IoT platform. ThingSpeak was selected as it is one of the IoT platform service pioneers.

There are many additional service ecosystems created by developers for the platform over the years, one of which is the Virtuino mobile application. Virtuino allows users to extract and view data stored in the ThingSpeak IoT platform in a simple-to-read manner using smart devices. Lastly, as shown in Fig. 6, the microcontroller was connected to the solar power bank for power supply, and the case was screwed together.

Features of the system

- Portable data acquisition unit: Fully wireless and self-powered sensor device.
- Weatherproof data acquisition unit: rugged and water-resistant enclosure for sensors.
- Remote monitoring: View the agriculture field and crop status from anywhere in the world.
- Simple-to-use: Plug-and-play data acquisition system with easy to navigate online IoT platform.
- WSN-ready: Deploy multiple data acquisition units for increased monitoring range.

Results and discussion

Stress–strain analysis

The data acquisition unit case was designed to be rugged and water-resistant for use in the open fields under harsh

Fig. 6 **a** Wiring of components, **b** fully assembled prototype data acquisition unit

conditions such as extreme heat, heavy rain, animal bites, and damage from farm equipment such as tractors and harvesters. Stress analysis was conducted on the CAD model to ensure rigidity and strength of the data acquisition unit enclosure and to prevent breakage under an applied force or load.

From Fig. 7, the stress analysis revealed that there were no significant weak spots in the case design and that the case should be able to withstand an upward force of 500 N, or a load of approximately 50 kg.

Functionality analysis

The system was tested to ensure that it can capture the environmental data via sensors and broadcast the information to the IoT platform. The data acquisition unit was connected to a local Wi-Fi network for testing purposes. The ThingSpeak IoT platform was accessed via an online webpage. The system was run for a few minutes to obtain multiple data entries.

It was observed that the environmental parameter readings captured by the sensors were successfully uploaded to the IoT platform. The data entry points were marked in four graphs, namely temperature, humidity, light intensity, and soil moisture graphs based on the corresponding information captured by the sensors, as shown in Fig. 8. The information was uploaded to the IoT platform once every 15 to 20 s.

The graphical representation of information provided by ThingSpeak provides better understanding of the relationship of environmental parameters relative to time. For example, as shown in Fig. 8, as the temperature decreases slightly with time, the humidity on the other hand increases with time. By studying these data trends, field managers can make better informed decisions regarding their crops based on the ambient conditions, thus further contributing to improved precision agriculture operations.

Consequently, the Virtuino mobile application was also tested to ensure that it can extract and display the environmental parameter information stored in the cloud server in an easily readable format. From Fig. 9, it was observed that the application successfully displayed the required data. The application also sounded an alarm to alert users when the user-defined threshold for each parameter was exceeded.

Next, the data acquisition unit was tested for water resistance. This was to ensure that the device can be used for outdoor or open-field applications. The device was first run under tap water, and no leaks were recorded. Next, the device was run under a shower to simulate a heavy downpour. Unfortunately, water ingress was detected at the top part of the case, at the joint between the acrylic panel and case, as well as at the top and bottom part joints. This was due to the O-ring not functioning as expected to keep the water out, and in part due to the poor surface quality of the 3D-printed parts. The rough surface of the parts does not provide a watertight seal when the rubber O-ring was placed in the designed channel. However, proper manufacturing of the case via a plastic molding technique can overcome this issue. As the device was still in the prototype phase, this issue was only deemed a minor setback which can be corrected easily in future revisions.

The battery life of the device was also tested to ensure that it can function continuously via solar power alone without the need to recharge the device. The solar panel was first covered up and not exposed to sunlight in order

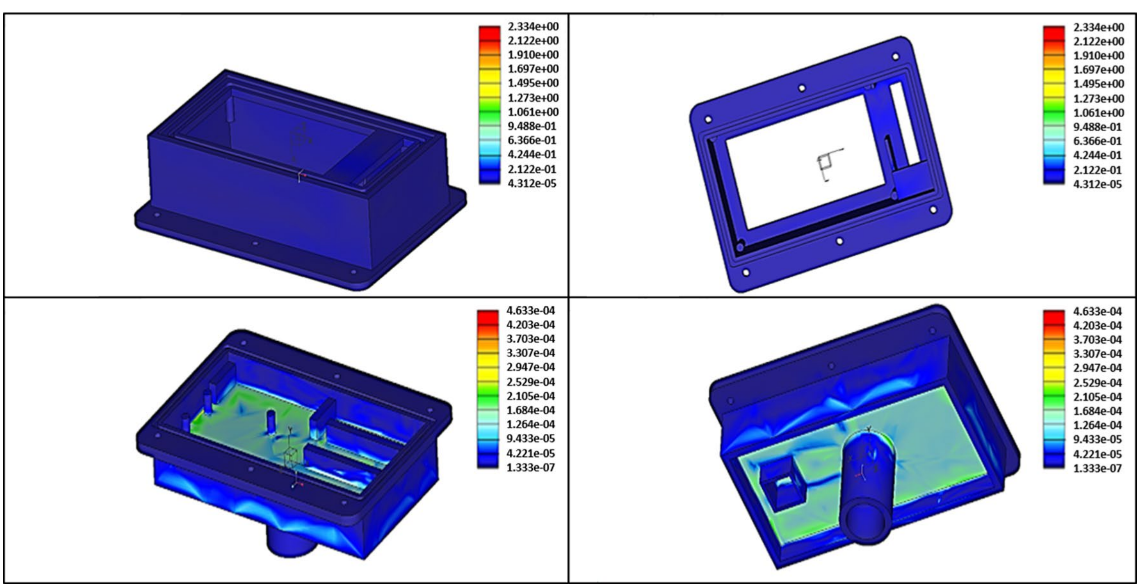


Fig. 7 Stress–strain analysis of case design

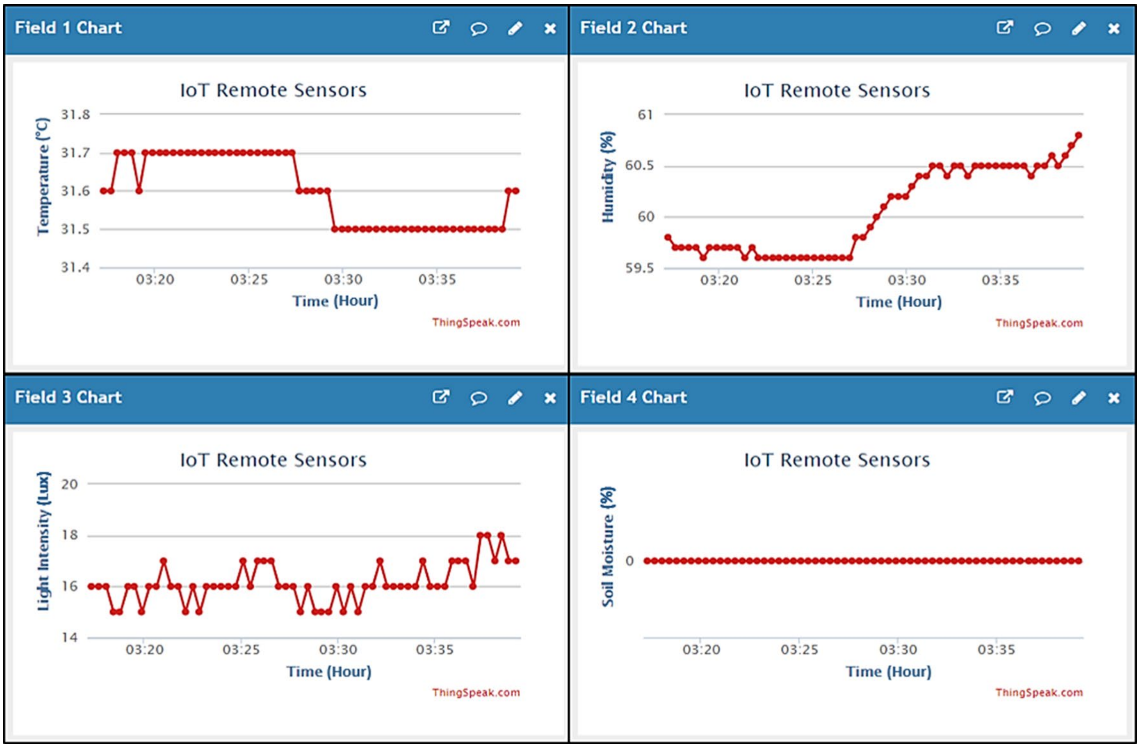


Fig. 8 Environmental parameter data on ThingSpeak IoT platform

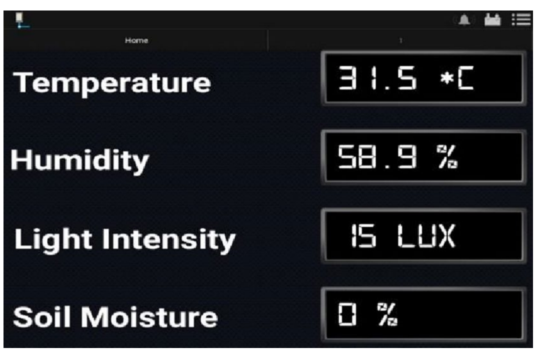


Fig. 9 Environmental parameter data on Virtuino mobile application

to simulate a worst-case scenario of continuously dark and cloudy days. The 12,000 mAh power bank managed to keep the device powered on for 16 days before finally going empty. Thus, in conditions where there is no sunlight, the device will continue to function for over two weeks. Next, the solar panel was exposed to sunlight under normal conditions and left to run for two months. By trickle charging the power bank during the day via the solar panels, the battery pack was still fully powered after the two months. Thus, under normal conditions, the setup is sufficient to power itself continuously without any issue.

On-site analysis

As this research work was conducted in collaboration with the Malaysian Agricultural Research and Development Institute (MARDI), the on-site test was carried out in a full-scale greenhouse measuring 40 ft by 100 ft provided by MARDI. This test was conducted to ensure that the device can perform as required under real-world daily usage conditions. The prototype data acquisition unit was switched on and staked into the ground of the greenhouse, as shown in Fig. 10.

The device was able to successfully capture and broadcast the environmental data as expected. The light intensity sensor was also closed, while water was poured into the ground to simulate a change in environmental conditions. The device managed to sense these changes without issues, as shown in Fig. 11.

However, one issue determined from the prototype testing was the wireless connection range. As this test was conducted by connecting the prototype of data acquisition unit to a Wi-Fi network provided via wireless hot spot from a mobile phone, the device would lose the connection and stop broadcasting information to the IoT platform when moved approximately 5 m apart from the device. This issue could be resolved by deploying wireless access points (WAP) in the field, which form a wireless local area network (WLAN), as this is the preferred wireless communication method for

Fig. 10 Prototype data acquisition unit test in full-scale greenhouse

a full-scale deployment of the system. One WAP deployment can provide an improved wireless network range of up to 0.5 km.

Performance analysis

Further testing was conducted to determine the usefulness of this agriculture monitoring system. For the performance test, the environmental information captured by the prototype data acquisition unit was utilized to automate the control systems to ensure optimum crop growth.

For the performance test, a small-scale greenhouse model was constructed to observe if the agriculture monitoring system can monitor the greenhouse conditions using the data acquisition unit and maintain the environmental parameters via the automation of control systems. The small-scale greenhouse, measuring $60 \times 60 \times 60$ cm, was fabricated using a wooden frame and acrylic panels. The temperature and humidity control system consisted of an intake and exhaust fan, the lighting system consisted of an LED light strip, and the irrigation system consisted of a water pump and tank. The information captured by the data acquisition system was used to automatically switch on and off the control system actuators using relays, based on user-defined thresholds. The small-scale greenhouse with corresponding data acquisition unit and control systems were powered directly from an electrical outlet socket via a 12 V 3A DC power adapter with a rated power consumption of 36 W.

Three areas were tested extensively, namely monitoring system test, control system test, and plant growth performance test. For monitoring system test, the environmental parameters, namely temperature, humidity, light intensity, and soil moisture readings captured by the data acquisition unit, were compared with the readings from standalone, off-the-shelf sensors, as shown in Fig. 12. This test can determine the accuracy and reliability of the data acquisition unit.

The control system test was conducted to determine if the system can utilize the environmental information captured by the data acquisition system to automate the control systems in agriculture. This is vital as the control system must maintain the greenhouse environmental parameters at appropriate levels for optimum plant growth. Failure of the control system would ultimately lead to unfavorable conditions for plant growth. The IoT functionality and automation of ventilation fans, LED lights, and water pump were tested.

Readings for the monitoring and control system tests were recorded both in the morning at 10:00 am and at night 10:00 pm, as presented in Fig. 13, two days once, over a

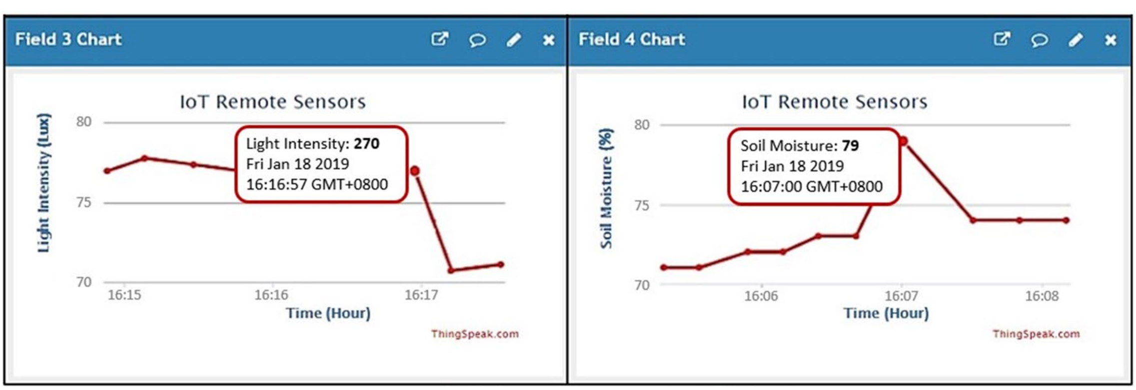


Fig. 11 On-site analysis data

Fig. 12 **a** Digital thermostat, **b** analogue three-way meter

Fig. 13 Small-scale greenhouse analysis in the morning and at night

period of 31 days. The test readings were recorded twice a day to account for the significantly different environmental conditions during these two times of the day.

Lastly, the plant growth performance test can determine if the agriculture monitoring system could be used to improve the crop growth and output via precision agriculture methods. For the plant growth performance test, the growth rate and performance of a test plant that was placed inside the small-scale greenhouse with the automated control system was compared to a base plant that was left outside in the open. The test plant was left completely under the care of the monitoring and control system in the small-scale greenhouse, while the base plant was attended to manually. The base plant was placed beside the small-scale greenhouse, as shown in Fig. 14, to eliminate other variables such as wind factor and shade. The base plant was watered manually every morning at 9:00 am with a volume of 400 ml. The readings of the plant parameters were recorded every other day for growth performance comparison including plant height, leaf length, and leaf width.

Lime plants were selected for this test as they grow well in local climate and are sensitive to the changes in environmental conditions. Therefore, improved growth performance, if any, by placing the plant in the small-scale greenhouse could be easily observed. Furthermore, lime plants have large leaves that can be easily measured. Additionally, as lime plants are fruiting plants, the quality of fruits produced by the test and base plants could be observed as a further test to determine the growth performance of the plants. Lime plants thrive in a suitable temperature range of around 32 to 35 °C, along with a suitable soil moisture content range of 60% to 80%. The thresholds at which the

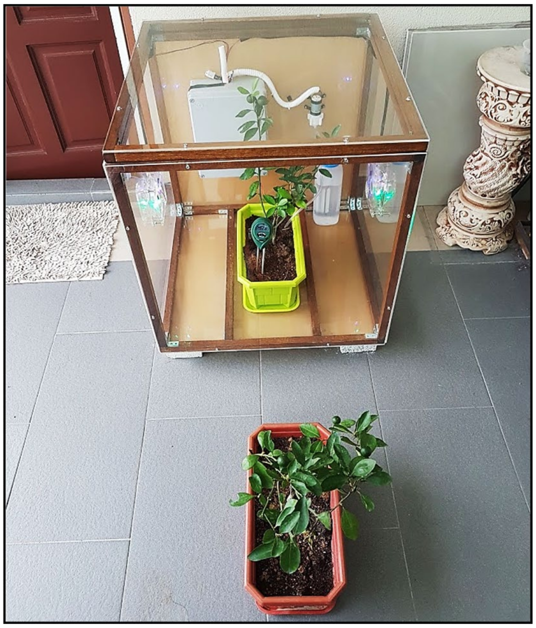


Fig. 14 Arrangement of test and base plants

automated control system switches on or off were set based on the requirements of the lime plant. The ventilation fans were set to switch on if the temperature exceeded 32 °C, the LED lights were set to switch on if the light intensity level dropped below 50Lux, and the water pump was set to switch on if the soil moisture content dropped below 60%.

From the monitoring system test results presented in Table 1, the temperature and humidity test readings closely matched the corresponding base readings with little error. As far as the light intensity readings were concerned, a larger variance was recorded between the test and base values. This was due to the lack of precision from the analogue three-way meter which has a light intensity range between 0 to 2000 lx on a small display scale.

Similarly, for soil moisture level, the three-way meter consists of a scale with 10 points, with 1 point representing 10%, ranging from dry to wet. Thus, most of the time, the base readings were approximated from the scale, which could have led to errors. However, even with these limitations, the test and base readings did not have too large of a variance, as shown from Fig. 15. Thus, it could be concluded that the data acquisition system is sufficiently accurate and reliable.

As for the control system test, from Table 2, it was recorded that the ventilation fans were running in the morning and switched off at night. This was inversely true for the LED lights, which were switched off in the morning and running at night. As for the water pump, it was not running when results were recorded. However, the soil moisture readings in the greenhouse remained at appropriate levels throughout the testing period, and the water level inside the water tank was reduced by approximately 500 ml every two days once, with the tank being refilled eight times during the testing period. This indicated that while the water pump was not recorded to be running, it was working as expected. Thus, the automated control system managed to successfully maintain all the parameters within a suitable range.

From the results of the plant growth performance test in Table 3, the height increase in the test plant was much greater than the base plant. The test plant grew in height by 9 cm compared to 1 cm on the base plant. This was also the case with the leaf length and width, which showed a greater increase compared to the base plant. The leaf length and width of the test plant grew by 0.8 cm and 0.5 cm, respectively, compared to 0.5 cm and 0.2 cm of the base plant.

The improvement in plant growth performance of the test plant compared to the base plant can be better observed through graphical representation. As shown if Figs. 16, 17 and 18, the rate of growth of plant height, leaf length, and leaf width is much greater in the test plant compared to the base plant.

Furthermore, observation of the two plants also determined that the test plant looks much healthier with brighter leaves, increased growth of new shoots, and juicier lime fruits produced compared to the base plant. The leaves of the base plant were of a very dark shade of green compared to the brighter shade on the test plant. This would indicate an increased amount of chlorophyll in the base plant due to inadequate lighting. This, in turn, proves that the LED lights in the small-scale greenhouse can supplement plant growth on days where there is inadequate lighting available to the plant.

Growth of new shoots and improved fruit quality also proves that the test plant inside the greenhouse was in much better condition compared to the base plant. Thus, the agriculture monitoring system can provide various benefits such as automation of agricultural systems and improved crop growth performance.

Conclusion

The objective of this research work was to develop an improved agriculture monitoring system that overcomes issues of previous systems, including cost, coverage range, and outdoor usability. A simple, low-cost, wireless precision agriculture monitoring system that is highly portable and rugged for outdoor use, self-powered to reduce the need of extensive cabling for power supply, while providing additional functionality that reduces agriculture workload and increases crop yield and profits was developed. Tests conducted on the prototype of data acquisition unit showed that it could perform as required under laboratory conditions in

Table 1 Monitoring system test

Day	Time	Test readings				Base readings			
		T	H	L	S	T	H	L	S
1	10 am	34.3	62.9	481	64	35.0	64.7	500	65
	10 pm	30.6	59.2	33	62	30.8	60.1	40	65
3	10 am	33.6	61.7	454	62	34.3	62.6	500	65
	10 pm	30.3	58.4	28	61	30.7	59.8	40	65
5	10 am	34.1	62.2	483	63	34.9	63.8	500	65
	10 pm	30.4	58.8	25	61	31.0	59.6	40	60
7	10 am	34.5	64.1	488	61	35.1	66.2	500	60
	10 pm	30.6	59.1	31	62	31.2	60.3	40	60
9	10 am	34.8	64.5	501	61	35.6	67.2	500	60
	10 pm	31.0	59.0	36	61	31.5	60.2	40	60
11	10 am	34.7	64.3	479	62	35.4	66.7	500	60
	10 pm	31.2	59.6	29	61	31.8	61.4	40	60
13	10 am	34.2	63.8	492	62	34.9	65.3	500	60
	10 pm	30.8	59.2	32	62	31.3	60.8	40	60
15	10 am	34.4	64.4	464	61	35.1	66.5	500	60
	10 pm	30.7	59.5	33	61	31.2	61.9	40	60
17	10 am	34.6	65.2	471	61	35.4	68.1	500	60
	10 pm	31.0	60.1	29	63	31.8	62.2	40	65
19	10 am	34.1	64.8	468	61	34.9	67.4	500	65
	10 pm	30.7	59.8	30	62	31.3	62.7	40	65
21	10 am	33.9	63.9	442	62	34.6	65.8	500	60
	10 pm	30.3	58.7	33	61	30.7	60.5	40	60
23	10 am	34.2	64.2	468	62	35.0	67.3	500	60
	10 pm	30.8	59.1	35	62	31.4	61.0	40	60
25	10 am	34.0	64.1	457	63	34.8	66.9	500	65
	10 pm	30.5	58.3	31	62	30.9	60.7	40	60
27	10 am	34.5	65.0	482	62	35.1	68.3	500	65
	10 pm	31.1	59.2	33	62	31.6	61.4	40	65
29	10 am	34.3	64.9	473	61	34.8	67.8	500	60
	10 pm	31.2	59.3	29	62	31.6	61.2	40	60
31	10 am	34.6	65.1	479	61	35.2	67.6	500	60
	10 pm	30.9	59.4	32	62	31.3	61.4	40	60

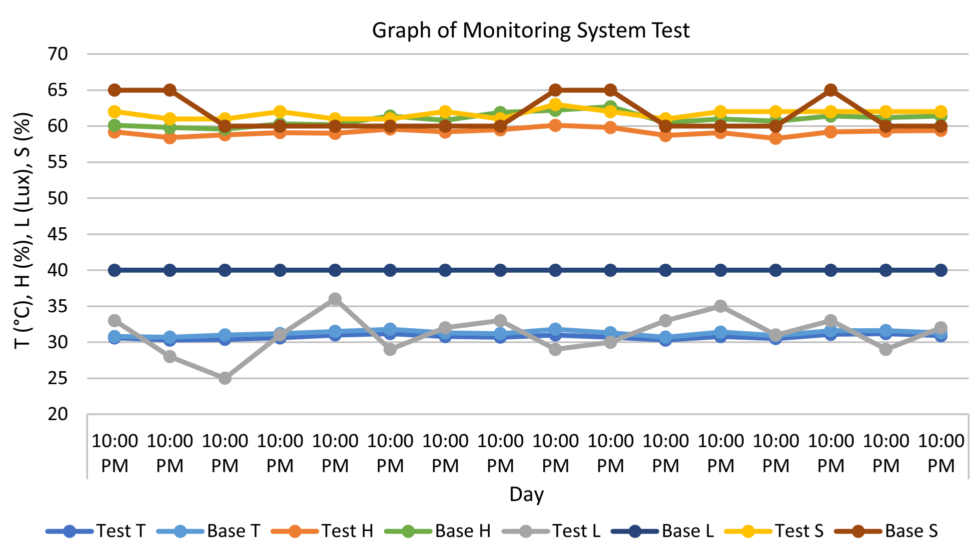


Fig. 15 Graph of monitoring system test

Table 2 Control system test

Day	Time	IoT	Control system			
			Fan 1	Fan 2	Lights	Pump
1	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
3	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
5	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
7	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
9	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
11	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
13	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
15	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
17	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
19	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
21	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
23	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
25	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
27	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
29	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off
31	10 am	On	On	On	Off	Off
	10 pm	On	Off	Off	On	Off

a small-scale greenhouse model. The data acquisition unit consisting of sensors and microcontroller could successfully capture the environmental parameter data such as temperature, humidity, light intensity, and soil moisture content. Next, by utilizing the IoT technology, the information captured by the sensors was uploaded wirelessly to the cloud server to be viewed by users via an Internet-enabled device. This information is useful for the field managers to distribute resources, produce predictive models for crop growth, and automate farming equipment. This leads to efficient agricultural operations and use of resources, reduced running cost and workload, and improved crop productivity. The WSN system developed in this research work provides an improved monitoring range, while the rugged, weatherproof solar-powered data acquisition unit was found to be suitable for extended outdoor use. Furthermore, the monitoring system test determined the accuracy of the data acquisition unit while the automation of control system via monitoring of environmental parameters was determined to be reliable at maintaining the conditions inside the small-scale greenhouse for optimum plant growth. The plant growth performance test showed a noticeable improvement in plant growth performance due to the agriculture monitoring system. As such, the agriculture monitoring system developed for this research work can reduce resource usage, labor requirements, and operational costs, while at the same time improving crop health and productivity. While the project has been a success, there are several recommendations identified for future work. Issues from the prototype model can be resolved via improved manufacturing techniques such as plastic molding for case production. Next, the system can be made to be interactive by displaying different environmental

Table 3 Plant growth performance test

Day	Test Plant			Base plant		
	Plant height	Leaf length	Leaf width	Plant height	Leaf length	Leaf width
1	39	5.7	2.8	43	6.2	3.0
3	39	5.7	2.8	43	6.2	3.0
5	40	5.8	2.8	43	6.2	3.0
7	41	5.8	2.9	43	6.3	3.0
9	42	5.9	2.9	43	6.3	3.0
11	42	6.0	3.0	43	6.4	3.0
13	42	6.0	3.0	43	6.4	3.0
15	43	6.1	3.0	43	6.4	3.1
17	44	6.2	3.1	43	6.4	3.1
19	44	6.2	3.1	44	6.5	3.1
21	45	6.3	3.1	44	6.5	3.1
23	45	6.3	3.2	44	6.6	3.1
25	46	6.4	3.2	44	6.6	3.1
27	47	6.4	3.3	44	6.7	3.1
29	47	6.5	3.3	44	6.7	3.2
31	48	6.5	3.3	44	6.7	3.2

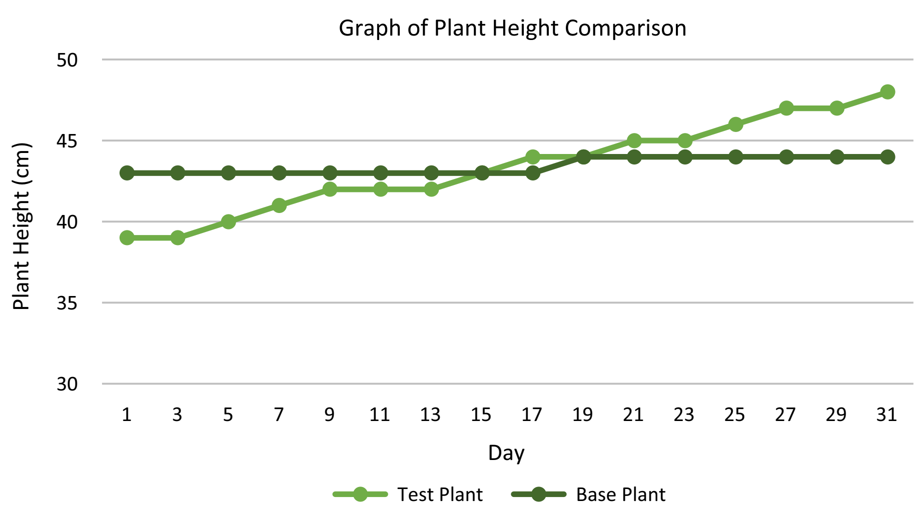


Fig. 16 Graph of plant height comparison

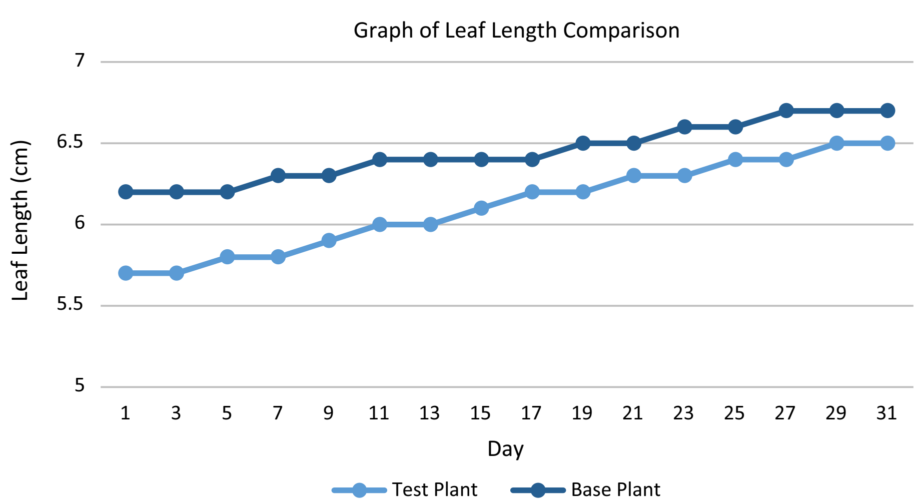


Fig. 17 Graph of leaf length comparison

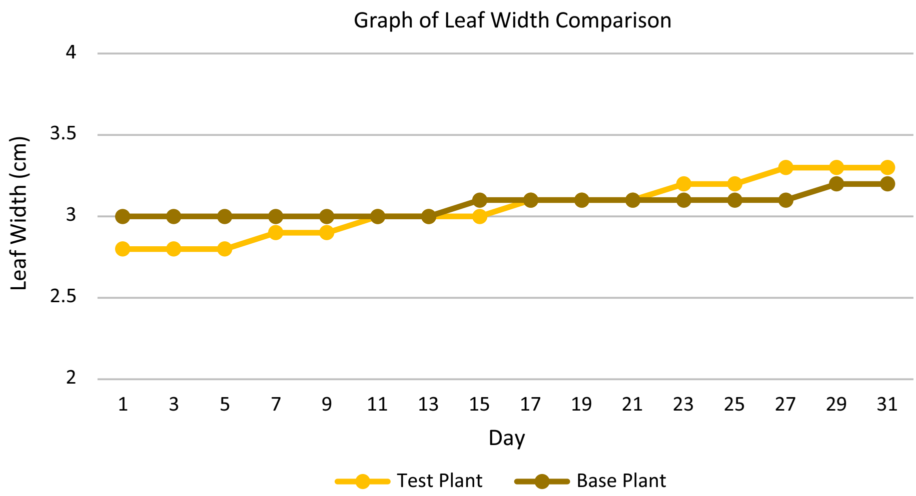


Fig. 18 Graph of leaf width comparison

conditions using LED lights. While the field managers can view the environmental parameter data on the IoT platform using an Internet-enabled device, this information will still have to be relayed to the site workers. Thus, interactive lights on individual data acquisition units can provide immediate alerts to the site workers.

Acknowledgements The authors would like to thank the Innovation & Research Management Centre (iRMC), and College of Engineering, UNITEN, for their continued support of this work. The authors would also like to thank the Malaysian Agricultural Research and Development Institute, MARDI, for their contribution of knowledge and resources towards this research work. Lastly, the authors would like to thank the Institute of Tropical Forestry and Forest Product (INTROP), UPM.

Funding This research was funded by the UNITEN Internal Grant 2018 (UNIIG2018), Number: J510050849 and Higher Education Center of Excellence (HICoE), Ministry of Higher Education, Malaysia.

Compliance with ethical standards

Conflicts of interest The authors declare no conflict of interest.

References

Adelantado F, Vilajosana X, Tuset-Peiro P, Martinez B, Watteyne T (2017) Understanding the limits of LoRaWAN. IEEE Commun Mag 55(9):34–40

Adila F, Bahaman A (2013) Factors impinging farmers' use of agriculture technology. Asian Soc Sci 9(3):120–124

Blandford D, Braden JB, Shortle JS (2014) Economics of natural resources and environment in agriculture. In: Van Alfen NK (ed) Encyclopaedia of agriculture and food systems. Elsevier Inc., Amsterdam, pp 18–34

Dagar R, Som S, Khatri SK (2018) Smart farming-IoT in agriculture. In: International conference on inventive research in computing applications 2018, pp 1052–1056

Davcev D, Mitreski K, Trajkovic S, Koteli N (2018) IoT agriculture system based on LoRaWAN. In: IEEE international workshop on factory communication systems 2018, pp 1–4

Deshpande P, Damkonde A, Chavan V (2017) The internet of things: vision, architecture and applications. Int J Comput Appl 178:1–14

Dinar A, Tieu A, Huynh H (2019) Water scarcity impacts on global food production. Glob Food Secur 23:212–226

Dursun M, Ozden S (2011) A wireless application of drip irrigation automation supported by soil moisture sensors. Acad J Sci Res Essays 6(7):1573–1582

Dwarkani C, Ganesh R (2001) Smart farming system using sensors for agricultural task automation.In: IEEE technological innovation in ICT for agriculture and rural development 2001, pp 49–53

Erbaugh J, Bierbaum R, Castilleja G, Hansen B (2019) Toward sustainable agriculture in the tropics. World Dev 121:158–162

Hajjaj SSH, Rao K (2019) Portable, wireless, and interactive system with internet-of-things and blockchain for agriculture field [Filed], UI2019005917

Hajjaj SSH, Sultan MTH, Moktar MH, Lee SH (2020) Utilizing the internet of things (IoT) to develop a remotely monitored autonomous floodgate for water management and control. Water 12(2):502

John GE (2016) A low-cost wireless sensor network for precision agriculture. In: International symposium on embedded computing and system design 2016, pp 24–27

Kalaivani T, Priya P, Allirani A (2011) A survey on ZigBee based wireless sensor networks in agriculture. In: International conference on trends in information sciences & computing 2011, pp 85–89

Kamilaris A, Gao F, Prenafeta-Boldu FX, Ali MI (2016) Agri-IoT: a semantic framework for internet of things-enabled smart farming applications. In: IEEE world forum on internet of things 2016, pp 442–447

Kavitha BC, Shilpa DP, Thanushree KS, Swathi AM, Ranjitha MK (2018) Agricultural crop monitoring using IoT-A study. Int J Eng Res Technol 6(13):1–4

Khanna A, Kaur S (2019) Evolution of internet of things (IoT) and its significant impact in the field of precision agriculture. Comput Electron Agric 157:218–231

Krishna KL, Silver O, Malende WF, Anuradha K (2017) Internet of things application for implementation of smart agriculture system. In: International conference on IoT in social, mobile, analytics and cloud 2017, pp 54–59

Kumar S, Kumar U (2015) Development of WSN system for precision agriculture. In: International conference on innovations in information embedded and communication systems 2015, pp 1–5
Ma Y, Chen J (2018) Toward intelligent agriculture service platform with LoRa-based wireless sensor network. In: IEEE international conference on applied system invention 2018, pp 204–207
Mat I, Kassim MRM, Harun AN (2015) Precision agriculture applications using wireless moisture sensor network. In: IEEE Malaysia international conference on communications 2015, pp 18–23
Mathurkar SS, Chaudari DS (2013) A review on smart sensors-based monitoring system for agriculture. Int J Innov Technol Explor Eng 2:352–355
Nandurkar SR, Thool VR, Thool RC (2014) Design and development of precision agriculture system using wireless sensor network. In: International conference on automation, control, energy and systems 2014, pp 1–6
Pallavi S, Mallapur JD (2017) Remote sensing and controlling of greenhouse agriculture parameters based on IoT. In: International conference on big data, IoT and data science 2017, pp 44–48
Palowski A, Guzman JL, Rodriguez F, Berenguel M, Sanchez J (2009) Simulation of greenhouse climate monitoring and control with wireless sensor network and event controller. Sensors 9:232–252
Patil KA, Kale NR (2016) A model for smart agriculture using IoT. In: International conference on global trends in signal processing, information computing and communication 2016, pp 543–545
Pradeep K, Byregowda BK (2017) Greenhouse monitoring and automation system using microcontroller. Int J Eng Trends Technol 45(5):196–201
Prathibha SR, Jyothi MP (2017) IoT based monitoring system in smart agriculture. In: International conference on recent advances in electronics and communication technology 2017, pp 81–84
Ramya R, Sandhya C, Shwetha R (2017) Smart farming systems using sensors. In: IEEE international conference on technological innovations in ICT for agriculture and rural development 2017, pp 218–222
Rehman A, Abbasi AZ, IslamN SZA (2011) A review of wireless sensors and networks applications in agriculture. Comput Standards Interfaces 36:263–270
Roselin R, Jawahar A (2017) Smart agro system using wireless sensor networks. In: International conference on intelligent computing and control systems 2017, pp 400–403
Silvade W, Borchardt A, Gabriellido D, Arun N (2019) Urban challenges and opportunities to promote sustainable food security through smart cities and the 4th industrial revolution. Land Use Policy 87:104065
Sonnino R, Tegoni C, Cunto A (2019) The challenge of systemic food change: Insights from cities. Cities 85:110–116
Sushanth G, Sujatha S (2018) IoT based smart agriculture system. In: International conference on wireless communications, signal processing and networking 2018, pp 1–4
Thornton K, Kristjanson P, Forch W, Barahona C, Cramer L, Pradhan S (2018) Is agricultural adaptation to global change in lower-income countries on track to meet the future food production challenge? Glob Environ Change 52:37–48
Ullah A, Ahmad J, Muhammad K, Lee MY (2017) A survey on precision agriculture: Technologies and challenges. In: International conference on next generation computing, Kaohsiung, Taiwan, 21–24 December 2017
United Nations. World population projected to reach 9.8 billion in 2050. https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html. Accessed 1 Oct 2019
Xiang X (2011)Design of fuzzy drip irrigation control system based on ZigBee wireless sensor network International conference on computer and computing technologies in agriculture 2011, pp 95–501
Xuemei L, Yuyan D, Lixing D (2008) Study on precision agriculture monitoring framework based on WSN. In: International conference on anti-counterfeiting, security and identification 2008, pp 182–185
Zhang N, Wang M, Wang N (2002) Precision agriculture-A worldwide overview. Comput Electron Agric 36:113–132