IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 18, 2020, accepted November 24, 2020, date of publication December 1, 2020, date of current version January 8, 2021.

Digital Object Identifier 10.1109/ACCESS.2020.3041597

Towards Smart Agriculture Monitoring Using Fuzzy Systems

NORAMALINA ABDULLAH[1], (Member, IEEE), NOOR AERINA BINTI DURANI[1], MOHAMAD FARID BIN SHARI[1], KING SOON SIONG[1], VICKY KONG WEI HAU[1], WONG NGEI SIONG[1], AND IR KHAIRUL AZMAN AHMAD[2], (Senior Member, IEEE)
[1]School of Electric and Electronic Engineering, Universiti Sains Malaysia, Engineering Campus, Penang 14300, Malaysia
[2]Faculty of Electrical Engineering, Universiti Teknologi MARA, Permatang Pauh 14000, Malaysia

Corresponding author: Noramalina Abdullah (eenora@usm.my)

ABSTRACT Conventional farming is labor-consuming and the need to continuously monitor crops can be a burden for farmers. By realizing the concept of smart farming based on Internet of Things (IoT) technology, farmers can use a mobile application to observe and monitor air humidity, air temperature, and soil moisture–factors that can affect plant growth. Furthermore, the use of timers to control the pumps in conventional watering systems is not always practical in real-life cases. This paper proposes a framework that enables advanced fuzzy logic to control a pump's switching time according to user-defined variables, whereby sensors are the main aspect of and contributor to the system. Our proposed idea offers great potential for excellent performance as an interface between the sensors as the input and the IoT as the output medium. A comparison is made between the proposed system and manual handling. The results prove that the water consumption and watering time has been reduced significantly.

INDEX TERMS Fuzzy logic, Internet of Things, sensors, monitoring system.

I. INTRODUCTION

Monitoring systems are used in the field to collect information on farming conditions (e.g., light intensity, humidity, and temperature) [1] with the aim of enhancing crop productivity. Internet of things (IoT) technology is a recent trend in numerous fields, including monitoring systems for agriculture [1]–[3]. In conventional farming, farmers need manual labor to handle crops and livestock, often leading to inefficient resource use. This downside can be addressed through the concept of smart farming, whereby farmers receive training in the use of IoT, access to the global positioning system (GPS), and data management capabilities to increase the quantity and quality of their products. The current project integrates advanced systems to offer a tool rooted in smart agriculture. The chili plant is here chosen as the agricultural product to be investigated. Hereby, we draw on the substantial advantages offered by fuzzy systems to manage the information provided by the sensors, constructing specific yet understandable fuzzy rules to achieve a decision-maker. The study also facilitates the development of a low-cost prototype through the fabrication of the mechanical components, adapts a solar panel platform as a standby power supply, and finally integrates the prototype with advanced IoT technology.

A few review studies [1]–[9] examined the implementation of artificial intelligence and the application of IoT for agricultural monitoring. In [1], the authors reviewed the research on automation and IoT, with a focus on flowers and leaves on botanical farms. A decision-making method was used for the identification and watering process, and they discussed the implementation of a fuzzy logic system to obtain information on the slope, color, and soil texture. In [2], the authors highlighted smart farming systems based on acquiring data and utilizing them to make optimized decisions, thereby reducing the costs and enhancing environmentally friendly practices. Fuzzy logic uses linguistic variables that fit well with the complexity of the challenges posed by the diversity inherent to agricultural decision-making.Another implementation of fuzzy modeling was conducted in [10], who used fuzzy control theory to identify fuzzy terminologies, such as 'High', 'Very high' and so on. The information was used to control the position of a bucket that was the receiver of a signal. Meanwhile, [11] developed an innovative fuzzy system to accurately grade leaf diseases, and [12] implemented a fuzzy

The associate editor coordinating the review of this manuscript and approving it for publication was Muhammad Zakarya.

inference system to estimate stem water potential. According to Dengel in [13], agriculture offers a vast application area for a wide variety of AI core technologies. For example, [14] designed a support system for decision-making using kiwi, corn, and potato plants as the input variables, while in [15], they developed a system that processed images to detect weeds based on a fuzzy logic decision-making system, thereby determining the optimum amount of herbicide to be used on a farm. Finally, researchers in [16] assembled a fuzzy irrigation decision-making system using a virtual instrumentation platform of sensors, data loggers, and LabVIEW.

The study in [17] optimized the supply of water to crops using fuzzy logic. This study also outlined the trends and development of the agricultural sector based on the use of expert systems. In [18], they studied fuzzy logic-based crop yield estimation under the consideration of three input parameters, namely temperature, humidity, and moisture. By subjecting these parameters to fuzzy arithmetic, a crisp value of yield was obtained. We referred to [19]–[21] to gain an overview of the use of sensors in agriculture. The research in [22] focused on different automated processes, like milking and feeding. Even though this article considered dairy farms, it is possible to apply this basic knowledge on the IoT in other farming infrastructures, leading to better production.

The study in [23] considered various technologies, especially in relation to the IoT, to make agriculture smarter and more efficient. For this purpose, wireless sensors, UAVs, cloud-computing, and communication technologies were thoroughly reviewed. Various extant IoT-based architectures and platforms are available for agriculture applications, and the review article in [24] explored the techniques that have been considered to improve the management of farms. Wired networks are more suitable for indoor scenarios, while wireless networks work well in both indoor and outdoor scenarios. Researchers in [25] have developed a fuzzy system in controlling the nutrition, pH values, and temperature at the vegetable farms. The results help them to adjust the content of nutrient and suitable pH with a specific time. Finally, in [26], the researchers aimed to acknowledge the level of soil's humidity, temperature, and status of power supply at the farm. They used fuzzy logic controller to attain the inputs. Even though researchers in [25] and [26] have claimed that they use IoT, they didn't share the final output on the captured windows of IoT application.

This research is aligned with the aim of long-life learning in engineering that has been inculcated by the university in that substantial knowledge was required during the process, from when the information was acquired until the development of the prototype and interaction within the IoT. The motivation of this architecture is to produce a smarter and better system for remote farming. Fuzzy logic was selected as the main interface to enable the plant and farm to 'speak' so that the farmer can know the exact conditions and which actions should be taken. Table 1 presents a compilation of all the references with their respective applications, architectures, and shortcomings. There are five sections in this paper, Section 1 presents an introduction to smart agriculture, including the surveys of the literature that served as a reference for this study. Section 2 outlines the fabrication of the mechanical components involved in this project. Section 3 briefly explains our proposed architecture and the software development related to the use of a fuzzy logic system as our decision-maker as well as IoT applications. Section 4 presents the results and related discussion. Finally, we conclude the study in Section 5.

A. RESEARCH CONTRIBUTION

In this study, we developed a new farming monitoring system that has a robust design, high accessibility, and wireless communication. The system was integrated by using the input from sensors, interpreting by fuzzy logic architecture, and using IoT as the interface with the end-user. Since our aim is to help the farmers, we tried to design the system to be more understandable to them without the need for complex theoretical background. We fully utilized the knowledge from fuzzy systems to provide input for the flow rate identification. Thus, the effectiveness of the process is improved compared to the traditional and manual appliances from the farmers. The major contribution of our research can be summarized as follows:

- A new finding on the effect of the flow rate, which is important for the farmers. The information from the finding will be the guidance for adjusting the specific flow rate, volume, and speed. The effect of flow rate will also be considered for the setting time in each process at the farm, for example, setting time for watering the plant. Thus, the monitoring can be more efficient.
- We have identified the relationship between the air temperature, air humidity, and soil moisture, and watering time. The information has been transformed into the IoT using the selected platform. The IoT tools were better modified than in the previous literature in terms of visibility and accessibility for the end-user. We also presented the windows of IoT application so that the readers can have a better understanding.

II. FABRICATION OF THE MECHANICAL COMPONENTS

The drawing of the prototypes was performed using Solidwork Design software. The structure of the master controller, presented in Fig. 1, was designed to fulfill the requirements set by the end-user. Some necessary elements are required for the master controller to perform well, including the power system (a power bank with a solar panel), breadboard, DHT11 sensor, capacitive soil moisture sensor, and NodeMCU (Node MicroController Unit) controller. The master controller was enclosed in a plastic casing, which had a size determined by the need to store all the necessary components; therefore, the dimensions of the casing for the whole master controller were 20 cm x 14 cm x 8 cm (length x breadth x height).

TABLE 1. Complexity analysis and state-of-art for reference.

Architecture	Application	Embedded system	Challenge
[1] Machine and deep learning	For flower and leaf identification and watering	Not related	Unable to consider lower and upper limits
[2] Modern data-based techniques	A review of agriculture data management practices	Not related	In-depth training needs to be delivered to the user
[3] Intelligent techniques	Monitoring and controlling in aeroponic systems	Wireless sensors	Understanding the nutrient parameters
[4] Fuzzy logic	Temperature and humidity plant disease forecasting	Not related	Fully linguistic variables
[5] Utilizing sensors	Smart water technology	Zigbee, smart meter	Handling huge data
[6] Support vector machine and fuzzy logic	Sorting and grading fruit	Not related	Visibility of image
[7] Expert system, fuzzy logic	Control of remedy measures	Not related	Vast information
[8] Fuzzy logic	Study on how to provide a balance of water and soil	Not related	More information about the system required
[9] Fuzzy system	Identifying the best cropping patterns in agriculture	Not related	Complex patterns to reduce pesticide use
[10] Fuzzy control	Controlling the position of the bucket	Not related	More experiments in different conditions
[11] Machine vision and fuzzy logic	Grading leaf diseases	Not related	Image enhancement
[12] Takagi–Sugeno–Kang fuzzy inference system	Estimating stem water potential	Not related	Making the models more interpret-able
[13] Multi criteria decision-making (MCDM) technique	Energy and environmental planning for electrification	Not related	Needs formulation to tackle diverse dimension
[14] Fuzzy decision support system.	Irrigation of timing and water saving	Not related	Maintaining the robust results
[15] Image processing as input for fuzzy logic	Identifying the optimum amount of herbicide	Not related	Efficiency of image recognition
[16] Fuzzy controller used for irrigation	Compensating for water loss via evapotranspiration	ZigBee, GPRS platform	Requires a stable network
[17] Fuzzy inference system	Identifying irrigation requirements	Not related	Precise information for rules development
[18] Fuzzy logic	Predicting the influence of climate variations	Not related	Detail needed of crisp value
[19] Control techniques for hydroponic systems	Identifying the exact amount and conditions of nutrient	Not related	Knowledge of planting techniques
[20] Sensing systems performance	Detection of feeding animals and observing cow positions	GPS	Accuracy of sensors
[21] Sensing systems performance	Review of sensor-based applications in agriculture	Not related	Quality of smart sensors
[22] Utilizing big data	Dairy farming	Sensors and IBM cloud	Adaptation of technology and versatile design
[23] Review of IoT applications in farming	Wireless sensors, cloud-computing, and communication technologies	Gateway, UAV, remote sensing satellites	Detailed guidance between researcher, engineers, and farmers
[24] Review on IoT applications in farming	Critical comparison of wired and wireless networks	Arduino, Raspberry, UAV, ESP	Lack of support for real-time reaction
[25] Fuzzy controller used for controlling and IoT	Information of nutrition, pH and temperature	Arduino	Need the best selection of light for better performance
[26] Fuzzy controller used for irrigation and IoT	Information of humidity, soil and status of power supply	GSM application	Early stage of IoT involvement

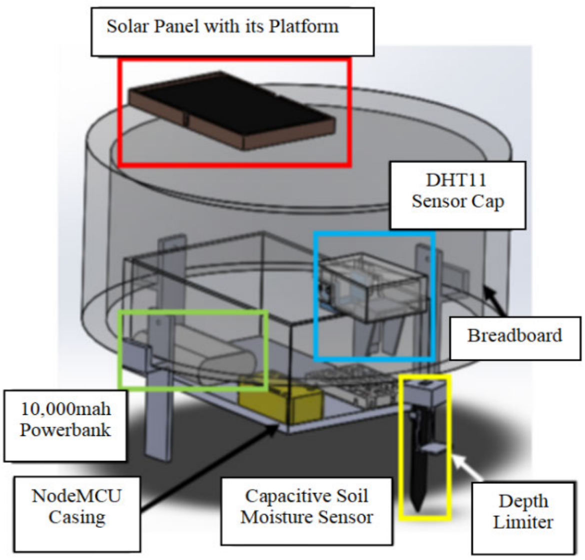

FIGURE 1. Solidwork design of the master controller prototype.

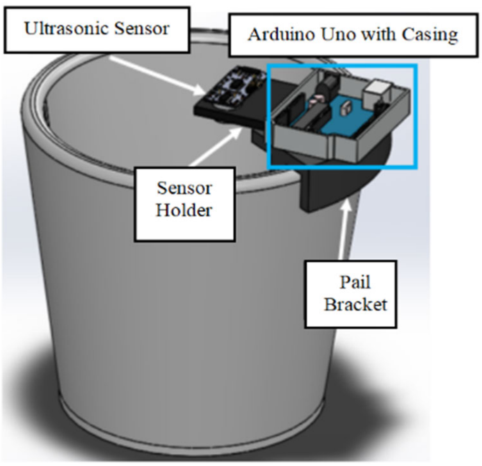

FIGURE 2. Solidwork design of the water leveling system prototype.

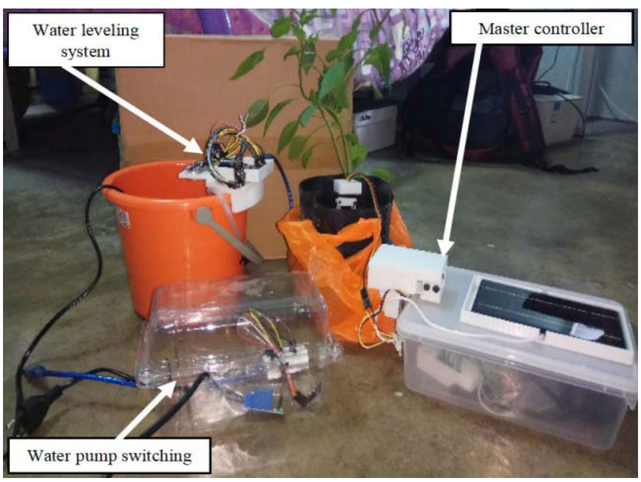

FIGURE 3. Overall system prototype.

The solar panel platform was designed to mount the solar panel on top of the casing. One of the important concerns while designing the platform was ensuring that the photovoltaic solar cell would be fully exposed to the sunlight. In other words, it had to be placed on top of the casing and have nothing blocking it. A hole was added to each side of the platform to allow the wire to exit the casing, with a placement chosen to prevent water from accumulating inside the platform during the rainy season. The capacitive soil moisture sensor was designed to include a depth limiter to

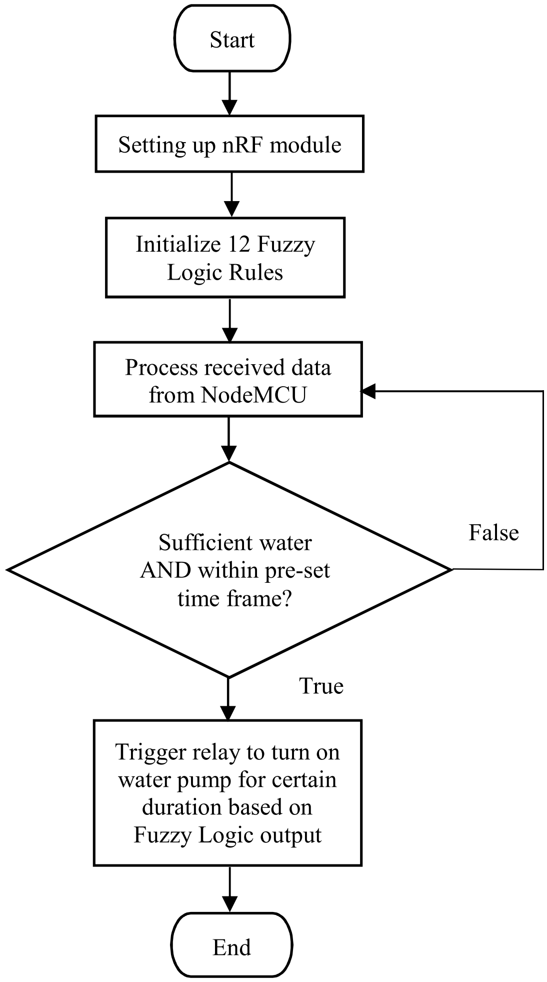

FIGURE 4. Flowchart for the watering system.

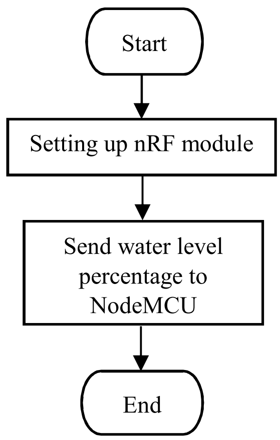

FIGURE 5. Flowchart for the water tank.

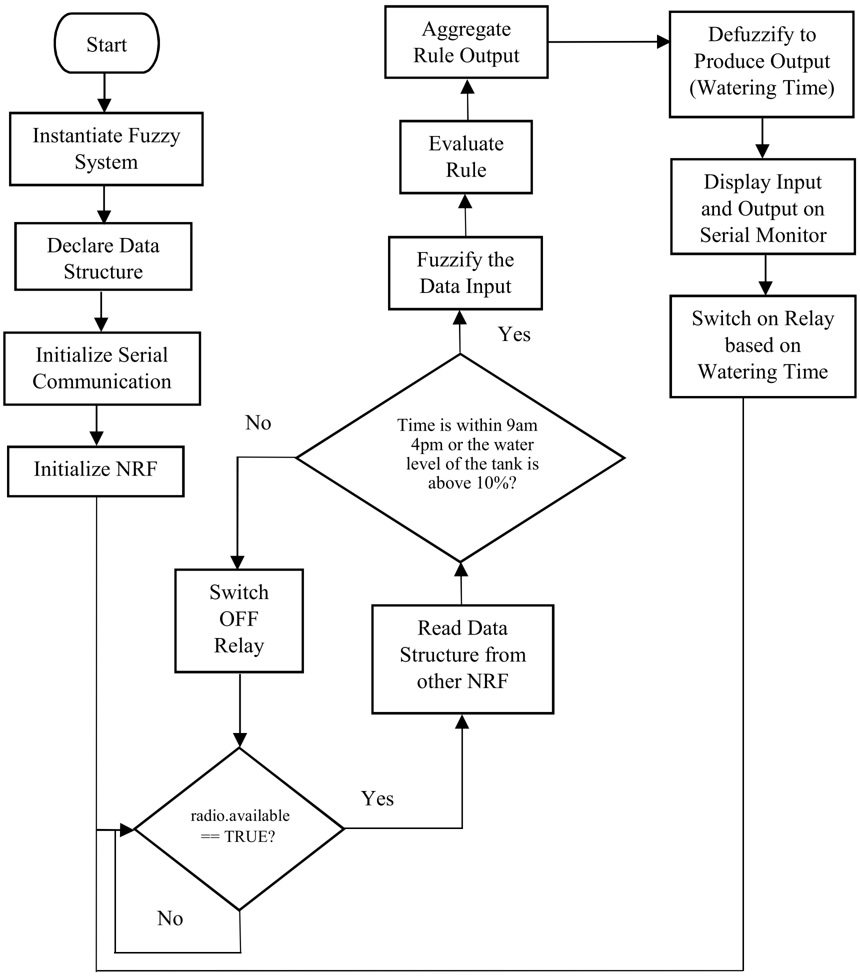

FIGURE 6. Flowchart for the switching controller.

prevent it from being inserted too deep into the soil, which would short the printed circuit board (PCB) on the upper part of the sensor. In addition, a cap was placed on top of the sensor to protect the PCB from rain. The DHT11 air temperature and humidity sensor was also protected by a cap, which was designed considering both the exposure of the sensor to the environment and the need to obtain accurate readings; hence, the eventual cap design was roof-like. Fitted with its cap, the sensor was attached to the cover of the casing. Lastly, the NodeMCU casing was designed to fix the position of the controller in the plastic casing to enhance the appearance and function of the prototype.

The water leveling system presented in Fig. 2 was used to simulate the measurement of the water level of a tank at the farm of the end-user. A pail bracket was fitted with a pail and a sensor holder, and its top was used to store the casing of an Arduino Uno. The bottom part of the Arduino Uno was also covered with the casing to prevent the pins underneath it from being directly exposed to the external environment, which would lead to a short circuit. A sensor holder was used to firmly hold the ultrasonic sensor to ensure consistent measurement of the water level. Finally, a shelter (not shown in the figures), built from a PVC basin with three 3D-printed stands fixed to the side, was placed above the master controller to shield it from the extreme conditions at the farm. The external diameter of the outer shelter was 35 cm, and the internal diameter was 31 cm. The three stands were used to lift the shield up and allow ventilation, thereby ensuring that the measurements taken by the DHT11 were accurate and similar to the surrounding conditions.

After the completion of the design phase, an overall system prototype was built. This was an important step that enabled us to examine a prototype as it would be used on the studied farm, but on a smaller scale. The overall system prototype setup is shown in Fig 3. Three subsystems were built, namely the master controller, the water leveling system and the water pump switching controller. Each of the subsystems included an NRF module. Several components of the prototype were 3D printed, including the cap and depth limiter of the capacitive soil moisture sensor, the solar panel platform, and the cap of the DHT11 air temperature and humidity sensor. The casing of the master controller was constructed from a purchased plastic container. The master controller contained various components, including the solar

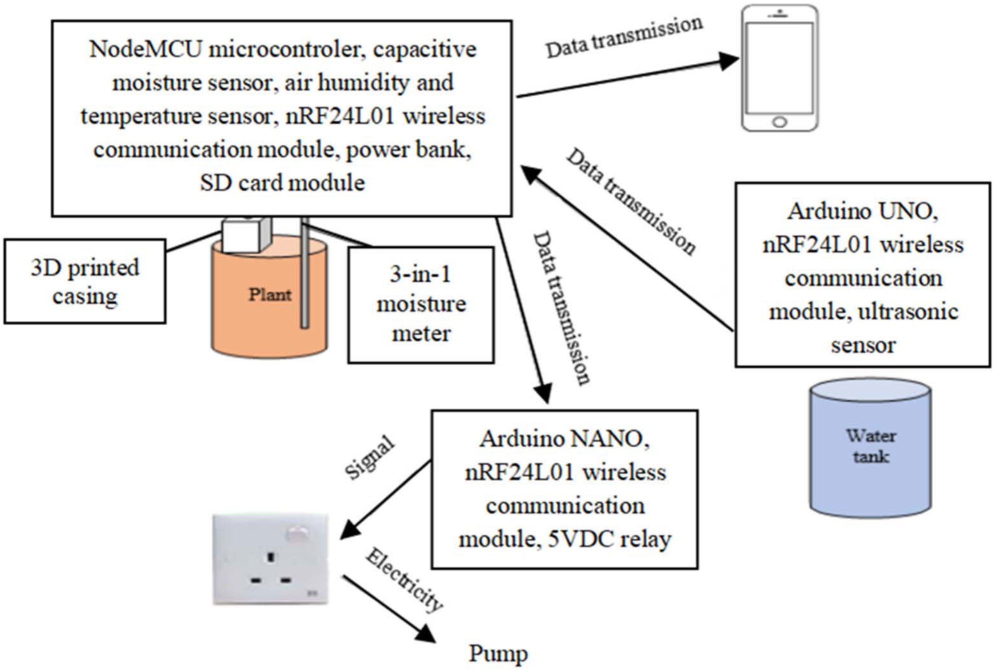

FIGURE 7. The communication between the subsystems.

panel, power bank, NodeMCU, DHT11, NRF module, and capacitive soil moisture sensor. The master controller was placed near the plant to accurately measure the immediate local environment.

A prototype of the water leveling system was built to simulate the water pump system existing at the chili farm. The structure of the prototype was built using a plastic pail, which acted as the water tank, a 3D printed ultrasonic sensor holder, and an Arduino Uno with its casing. An ultrasonic sensor was used to measure the water level, and the resulting data were sent by the NRF module to the master controller. The system power was supplied by a universal adapter connected to a three-pin plug. The water pump switching controller consisted of an Arduino Nano, a relay module, an NRF module, a universal adapter, and a water pump. The controller, relay module and NRF were shielded by a transparent plastic box to prevent the user from receiving an electro-shock as the system involved a high alternating current of 240 V. The flow charts presented in Figs. 4, 5 and 6 respectively explain the working system for each subsystem.

Three sensors were used in the hardware control units:

1. DHT11 air temperature and humidity sensor
2. Capacitive soil moisture sensor
3. Ultrasonic sensor

The Arduino Uno is a microcontroller board that, in terms of communication, offers many facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega328 provides UART TTL (5V) serial communication, which is available on digital pins 0 (RX) and 1 (TX). An ATmega16U2 on the board channels this serial communication over a USB and it appears as a virtual com port to software on the computer. The Arduino software includes a serial monitor, which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board flash when data are being transmitted via the USB-to-serial chip and USB connection to the computer. In the system developed here, it was used to control the ultrasonic sensor mounted above the water tank.

The Arduino Nano is a surface mount breadboard embedded version with integrated USB. The Arduino Nano offers several facilities for communicating with a computer, another Arduino, or other microcontrollers. The Arduino software includes a serial monitor, which allows simple textual data to be sent to and from the Arduino board. The RX and TX LEDs on the board flash when data are being transmitted via the FTDI chip and USB connection to the computer (but not for serial communication on pins 0 and 1). The Arduino Nano was used here to control the third nRF24L01 module, receiving the signal from the NodeMCU and Arduino Uno regarding the moisture level of the plants and the water level in the tank.

The capacitive moisture sensor is a soil moisture sensor based on capacitance changes. Compared with resistive sensors, capacitive sensors do not require the direct exposure of the metal electrodes, thereby significantly reducing the erosion of the electrodes. The DHT11 temperature and air humidity sensor features a temperature/humidity sensor complex with a calibrated digital signal output. By using the exclusive digital-signal-acquisition technique coupled with temperature and humidity sensing technology, it ensures high reliability and excellent long-term stability. This sensor includes a resistive-type humidity measurement component and an NTC temperature measurement component, and it

TABLE 2. Development of the fuzzy sets.

$\mu_{AH}^{Low}(x) = 0, \forall x \geq 85\%$	$\mu_{AH}^{Low}(x) = 1, \forall x \leq 70\%$
$\mu_{AH}^{High}(x) = 0, \forall x \geq 75\%$	$\mu_{AH}^{High}(x) = 1, \forall x \geq 90\%$
$\mu_{AT}^{Cool}(x) = 0, \forall x \geq 32°C$	$\mu_{AT}^{Cool}(x) = 1, \forall x \leq 24°C$
$\mu_{AT}^{Hot}(x) = 0, \forall x \leq 24°C$	$\mu_{AT}^{Hot}(x) = 1, \forall x \geq 34°C$
$\mu_{SM}^{Dry}(x) = 0, \forall x \geq 22$	$\mu_{SM}^{Dry}(x) = 1, \forall x \leq 10$
$\mu_{SM}^{Moderate}(x) = 0, \forall x \leq 13\ \&\ \forall x \geq 37$	$\mu_{SM}^{Moderate}(x) = 1, 22 \leq x \leq 28$
$\mu_{SM}^{Wet}(x) = 0, \forall x \leq 28$	$\mu_{SM}^{Wet}(x) = 1, \forall x \geq 40$
$\mu_{WT}^{VeryShort}(x) = 0, \forall x \geq 3$	$\mu_{WT}^{VeryShort}(x) = 1, \forall x \leq 0.75$
$\mu_{WT}^{Short}(x) = 0, \forall x \leq 1\ \&\ \forall x \geq 6$	$\mu_{WT}^{Short}(x) = 1, 3 \leq x \leq 4$
$\mu_{WT}^{Average}(x) = 0, \forall x \leq 4\ \&\ \forall \geq 11$	$\mu_{WT}^{Average}(x) = 1, 7 \leq x \leq 8$
$\mu_{WT}^{Long}(x) = 0, \forall x \leq 9\ \&\ \forall x \geq 14$	$\mu_{WT}^{Long}(x) = 1, 11 \leq x \leq 12$
$\mu_{WT}^{VeryLong}(x) = 0, \forall x \leq 12$	$\mu_{WT}^{VeryLong}(x) = 1, \forall x \geq 14$

connects to a high-performance 8-bit microcontroller, offering excellent quality, fast response, anti-interference ability and cost-effectiveness. The ultrasonic sensor is an instrument that measures the distance to an object using ultrasonic sound waves. It uses a transducer to send and receive ultrasonic pulses, which relay information about an object's proximity, whereby high-frequency sound waves reflect from the boundaries to produce distinct echo patterns.

Finally, the devices communicated with each other using single hop communication. The NodeMCU is an open-source software and hardware development environment that is built around a very inexpensive system-on-a-chip (SoC) called the ESP8266. The ESP8266, designed and manufactured by Espressif Systems, contains all the crucial elements of the modern computer: CPU, RAM, networking (Wi-Fi), and even a modern operating system. The ESP8266 integrates a 802.11b/g/n HT40 Wi-Fi transceiver, meaning it can not only connect to a Wi-Fi network and interact with the Internet, but it can also set up a network of its own, allowing other devices to connect directly to it. This makes the ESP8266 NodeMCU even more versatile. The NodeMCU was used to control the capacitive moisture sensor, air humidity, air temperature sensor, and SD card module. Meanwhile, as the nRF24L01 is a transceiver module, it can both send and receive data. For this project, three nRF24L01s were used to receive the signals from the ultrasonic sensor, communication for the 5VDC relay, and communication for the NodeMCU.

To summarize, three main subsystems were involved in the hardware system, namely the master controller, water leveling system, and water pump switching controller.

i. The master controller was equipped with a solar panel, air humidity and temperature sensor, breadboard, power bank, NodeMCU, capacitive soil and moisture sensor, and depth limiter.
ii. The water pump system was equipped with an ultrasonic sensor and Arduino Uno. Power was supplied by a universal adapter connected to a three-pin plug. The water pump was controlled by a water pump switching controller.
iii. The water pump switching controller consisted of an Arduino Nano, a relay module, an NRF module, a universal adapter, and a water pump.

TABLE 3. Development of the fuzzy rules.

Rule		
Rule 1	IF	Air Humidity is *Low*
	AND	Air Temperature is *Cool*
	AND	Soil Moisture is *Wet*
	THEN	Watering Time is *Short*
Rule 2	IF	Air Humidity is *Low*
	AND	Air Temperature is *Hot*
	AND	Soil Moisture is *Wet*
	THEN	Watering Time is *Long*
Rule 3	IF	Air Humidity is *High*
	AND	Air Temperature is *Hot*
	AND	Soil Moisture is *Wet*
	THEN	Watering Time is *Short*
Rule 4	IF	Air Humidity is *High*
	AND	Air Temperature is *Cool*
	AND	Soil Moisture is *Moderate*
	THEN	Watering Time is *Very Short*
Rule 5	IF	Air Humidity is *Low*
	AND	Air Temperature is *Cool*
	AND	Soil Moisture is *Moderate*
	THEN	Watering Time is *Short*
Rule 6	IF	Air Humidity is *Low*
	AND	Air Temperature is *Hot*
	AND	Soil Moisture is *Moderate*
	THEN	Watering Time is *Long*
Rule 7	IF	Air Humidity is *High*
	AND	Air Temperature is *Hot*
	AND	Soil Moisture is *Moderate*
	THEN	Watering Time is *Average*
Rule 8	IF	Air Humidity is *High*
	AND	Air Temperature is *Cool*
	AND	Soil Moisture is *Dry*
	THEN	Watering Time is *Average*
Rule 9	IF	Air Humidity is *Low*
	AND	Air Temperature is *Cool*
	AND	Soil Moisture is *Dry*
	THEN	Watering Time is *Average*
Rule 10	IF	Air Humidity is *Low*
	AND	Air Temperature is *Hot*
	AND	Soil Moisture is *Dry*
	THEN	Watering Time is *Very Long*
Rule 11	IF	Air Humidity is *High*
	AND	Air Temperature is *Hot*
	AND	Soil Moisture is *Dry*
	THEN	Watering Time is *Long*
Rule 12	IF	Air Humidity is *High*
	AND	Air Temperature is *Cool*
	AND	Soil Moisture is *Wet*
	THEN	Watering Time is *Very Short*

III. PROPOSED ARCHITECTURE AND SOFTWARE DEVELOPMENT

Fig. 7 demonstrates the communication between the subsystems. The Arduino Nano first initializes every necessary setup and declares any necessary variables. It then checks whether there are any incoming data by referring to the Boolean value returned from the radio.available() function. In our case, the relay switching controller receives data from the NodeMCU IoT platform through the NRF module. The data are sent and received in terms of structure. Fuzzy logic (FL) is a form of many-valued logic in that the software development starts with fuzzy logic utilization. The truth values of the variables may be any real number between 0 and 1, both inclusive. It is employed to handle the concept of partial truth, whereby the truth value may range between completely true and completely false. In addition, the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition.

Five variables are stored in the structure, namely air humidity, air temperature, water level, soil moisture and the hour of the current time. The Arduino Nano verifies the hour of the current time and the tank's water level before proceeding to the fuzzification of the input variables. This is because the plant does not require extra water to undergo photosynthesis before 9 am and after 4 pm. In addition, the water pump is not turned on if the water in the tank is not sufficient. If the time is within the pre-set timeframe and the water level is high enough, the air humidity, air temperature, and soil moisture will be processed as the inputs of the designed fuzzy system, giving the output in terms of watering duration. The output is used to set the duration for which the water pump will be turned on. The whole process is then repeated. All variables are separated as input and output respectively for the linguistic rules.

Input variables:

Air Humidity (AH) (Range: 50-100%)

Air Temperature (AT) (Range: 20-40°C)

Soil Moisture (SM) (Range: 0 ∼ 90 %)

Output variables:

Watering Time (WT) (Range: 0-15s)

Table 2 shows the development of the fuzzy sets and Table 3 shows the development of the fuzzy rules. Since a chili farm monitoring system consists of multiple multi-valued inputs and a single multi-valued output, fuzzy logic is used to make the system smarter. The setting of rules are important since it also need to consider the growth condtion of the chilli plant. Fuzzy logic is unlike two-valued Boolean logic as it can deal with a degree of membership and degrees of truth. It uses the continuum of logical values between 0 and 1. Instead of just true or false (Boolean), it can give a value between true and false, e.g. 0.4. The fuzzy system is designed based on the chili farm environment and the specifications of the water pump installed at the chili farm. Additional information from the farm caretaker is also taken into consideration to develop the fuzzy system, and Mamdani inference and the aggregation method are also employed. The defuzzification is done by finding the centroid.

The Arduino Integrated Development Environment (IDE) is a cross-platform application (for Windows, macOS, Linux) that is written in the functions of C and C++. It contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions, and a series of menus. In adapting IoT applications, three things need to be considered, namely the cost, usability and challenges; the resulting system can include real-time support and high bandwidths for excellent performance. Furthermore,

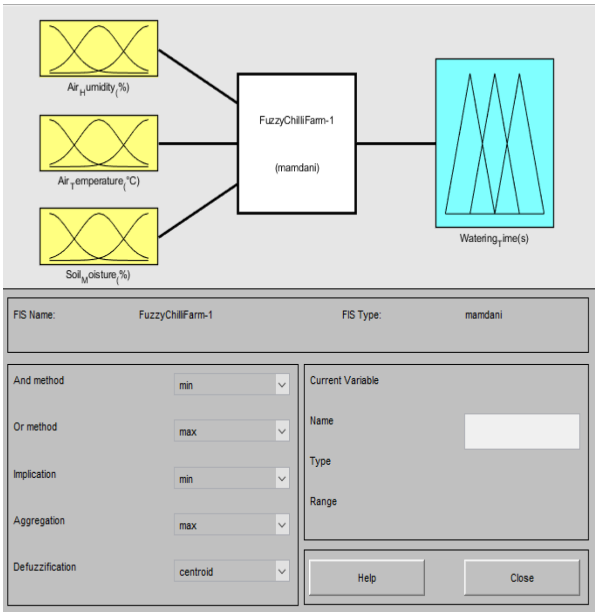

FIGURE 8. **Fuzzy inference system editor.**

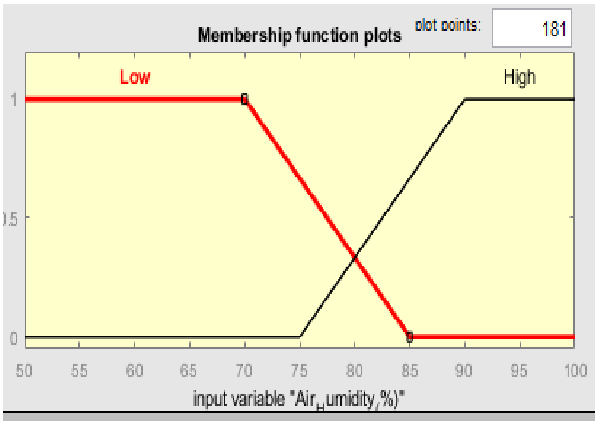

FIGURE 9. **The input variable of air humidity (%).**

in IoT solution architecture, four basic layers must be implemented;

I. Application, which involves plantation monitoring, disease controlling, irrigation, etc.
II. Processing, which concerns data storage, data filtering, data processing, etc.
III. Transport, which involves network protocols, application protocols, etc.
IV. Perception, which concerns the use of sensors, GPS, etc.

These platforms are implemented for a complete IoT architecture:

I. ThingSpeak

ThingSpeak is an open data platform for the IoT. Devices and applications can communicate with ThingSpeak using a RESTful API, and the data can remain private or be made public. ThingSpeak is used for diverse applications ranging from weather data collection and analysis to synchronizing the color of lights across the world. At the heart of

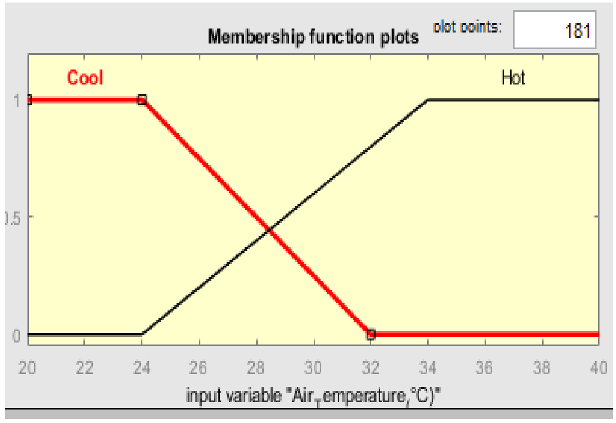

FIGURE 10. **The input variable of air temperature (°C).**

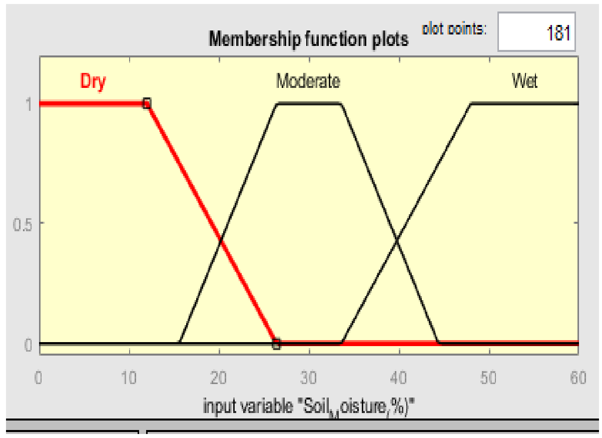

FIGURE 11. **The input variable of soil moisture level (%).**

ThingSpeak is a time-series database. ThingSpeak provides users with free time-series data storage in channels that can include up to eight data fields.

II. Open as App

Open as App is an Instant App Creator that allows Excel files or Google Sheets to be quickly turned into professional apps with high functionality both online and offline. It is even possible to implement automated app creation directly from business systems. This is a cloud-based service that turns calculations, lists, and forms into user-friendly apps that can be shared with a team, partners or clients on all major platforms. It is available for iOS, Android and UWP (Universal Windows Platform). The tool does not require any programming knowledge from the user and the resulting apps are available immediately.

III. Blynk

Blynk is an IoT platform designed to make the development and implementation of smart IoT devices quick and easy. It can be used to read, store, and visualize sensor data and control hardware remotely. It is also a control panel for visualizing and controlling hardware and is available for both Android and iOS. The app offers a very productive interface and various widgets for different purposes. It works on a currency of its own known as energy. There are two components

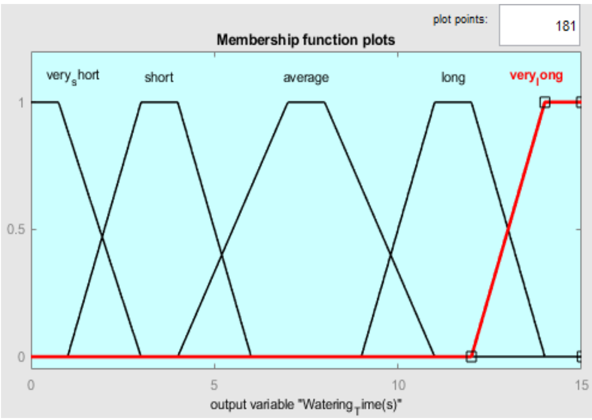

FIGURE 12. The output variable of watering time (s).

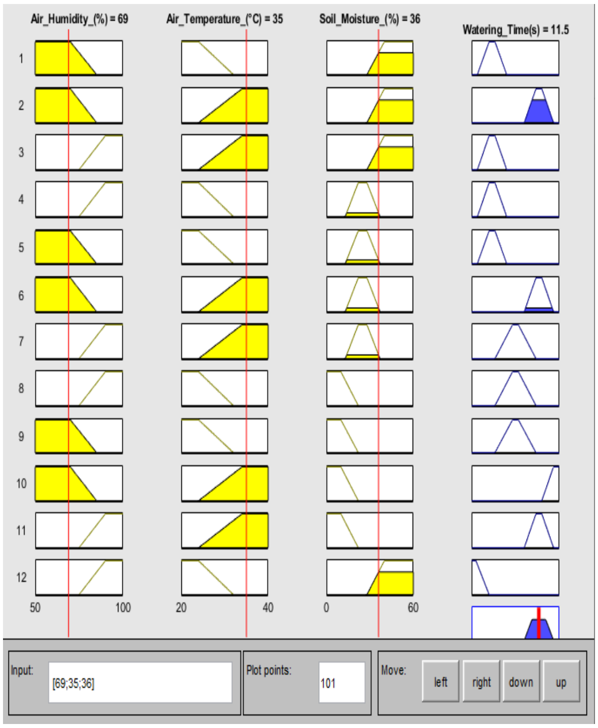

FIGURE 13. Rule viewers of the fuzzy system; air humidity = 69%, air temperature = 35°C, soil moisture = 36%.

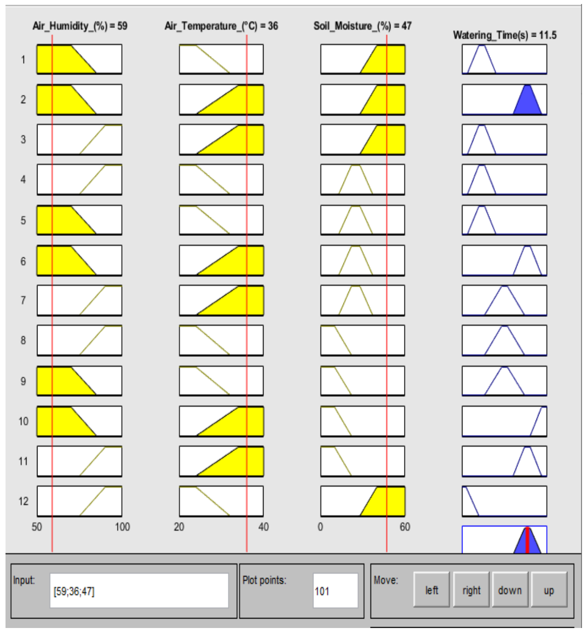

FIGURE 14. Rule viewers of the fuzzy system; air humidity = 59%, air temperature = 36°C, soil moisture = 47%.

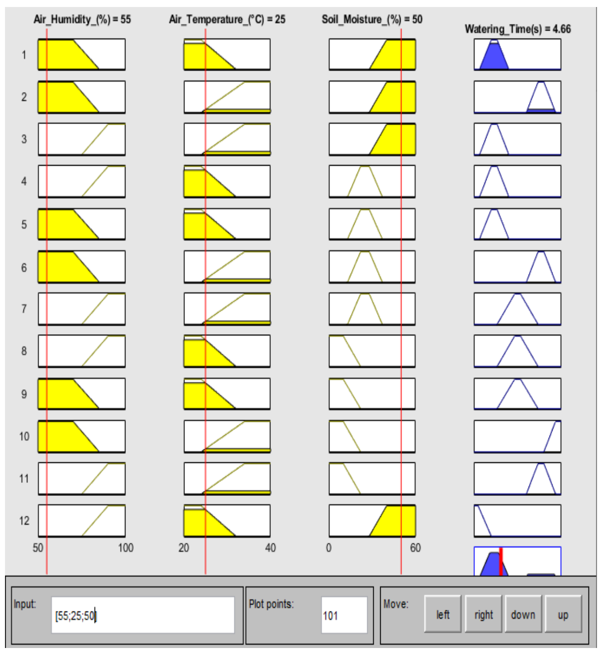

FIGURE 15. Rule viewers of the fuzzy system; air humidity = 55%, air temperature = 25°C, soil moisture = 50%.

in Blynk, namely Blynk Server and Blynk Library. Blynk Server offers a secure, responsive, and centralized cloud service through its server that allows communication between the devices. Blynk Server is also available as open source, enabling users to make their own servers and make them even more secure. Blynk Library facilitates the connection and operation of user hardware. The support for multiple hardware devices, including Arduino, ESP8266 and Raspberry Pi, is included in the library and this also makes it possible to connect these with hardware through, e.g., Wi-Fi, Bluetooth, BLE, USB and GSM.

IV. RESULTS AND DISCUSSION

Prior to examining the details of the fuzzy system, the range of possible values for the input and output variables must be identified. The trapezoidal membership functions implement the Mamdani method. There are three input membership functions in the developed fuzzy logic system, as shown in Fig 8. These are air humidity (%), air temperature (°C) and soil moisture level (%). The output membership function of the system is only the watering time (s). There are two membership functions, Low and High, for the input variable of air humidity, and there are also two membership functions, Cool and Hot, for the input variable of air temperature. The shape of the membership functions used for both input variables

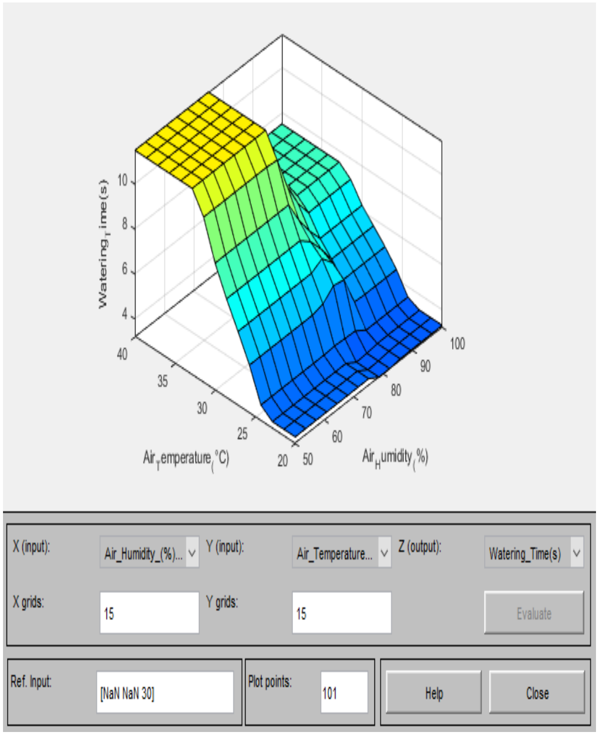

FIGURE 16. **Surface viewer of fuzzy system; input is air temperature; output is air humidity with watering time.**

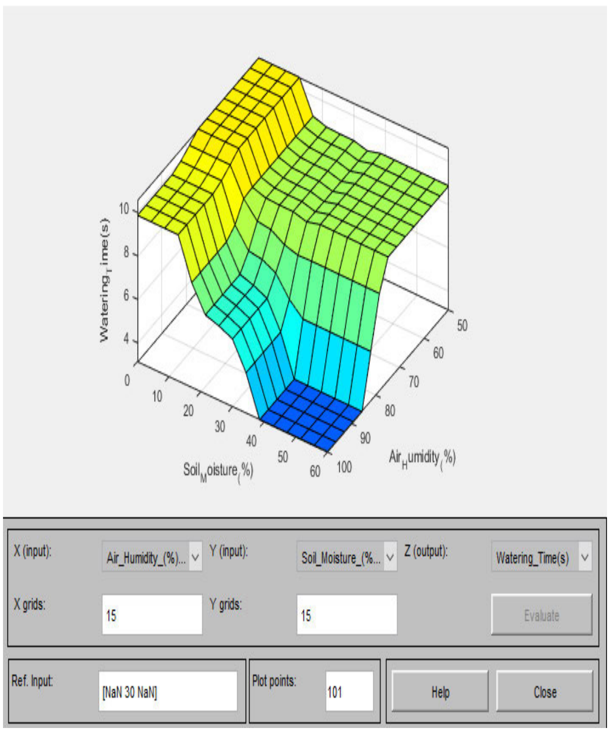

FIGURE 17. **Surface viewer of fuzzy system; inputs are soil moisture and air humidity; output is watering time.**

is a trapezium. The condition of the shape demonstrates the relationship between the variables. Figs. 9 and 10 describe the air humidity and air temperature input variables, respectively. Fig 11 shows the input variable of soil moisture level, which

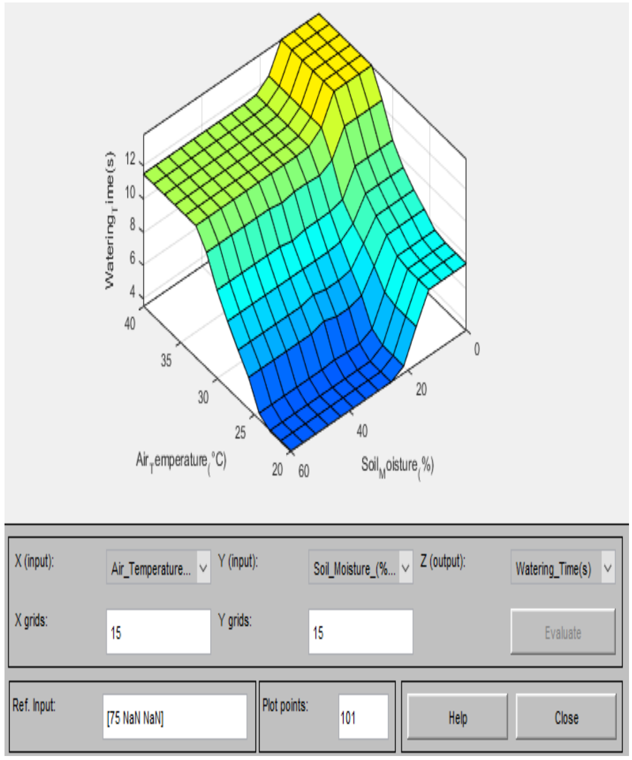

FIGURE 18. **Surface viewer of fuzzy system; inputs are air temperature and soil moisture; output is watering time.**

```
Entrance:
            Air Humidity: 69, Air Temperature 35, and Soil Moisture 36
Input:
      Air Humidity: Low-> 1.00, High-> 0.00
      Air Temperature: Cool-> 0.00,  Hot-> 1.00
      Soil Moisture: Dry-> 0.00, Moderate-> 0.11, Wet-> 0.67
Output:
      Watering Time: Very Short-> 0.00, Watering Time: Short-> 0.00, Average-> 0.00, Long-> 0.67, Very Long-> 0.00
Result:
            Watering Time: 11.50


Entrance:
            Air Humidity: 59, Air Temperature 36, and Soil Moisture 47
Input:
      Air Humidity: Low-> 1.00, High-> 0.00
      Air Temperature: Cool-> 0.00,  Hot-> 1.00
      Soil Moisture: Dry-> 0.00, Moderate-> 0.00, Wet-> 1.00
Output:
      Watering Time: Very Short-> 0.00, Watering Time: Short-> 0.00, Average-> 0.00, Long-> 1.00, Very Long-> 0.00
Result:
            Watering Time: 11.50


Entrance:
            Air Humidity: 55, Air Temperature 25, and Soil Moisture 50
Input:
      Air Humidity: Low-> 1.00, High-> 0.00
      Air Temperature: Cool-> 0.88,  Hot-> 0.10
      Soil Moisture: Dry-> 0.00, Moderate-> 0.00, Wet-> 1.00
Output:
      Watering Time: Very Short-> 0.00, Watering Time: Short-> 0.88, Average-> 0.00, Long-> 0.10, Very Long-> 0.00
Result:
            Watering Time: 4.66
```

FIGURE 19. **Results displayed on the Arduino serial monitor.**

has the three membership functions of Dry, Moderate and Wet. The membership functions are also designed in the trapezium shape.

The output variable of watering time, as shown in Fig. 12, consists of three membership functions, namely Very Short, Short, Average, Long and Very Long, with the shape of a trapezium.

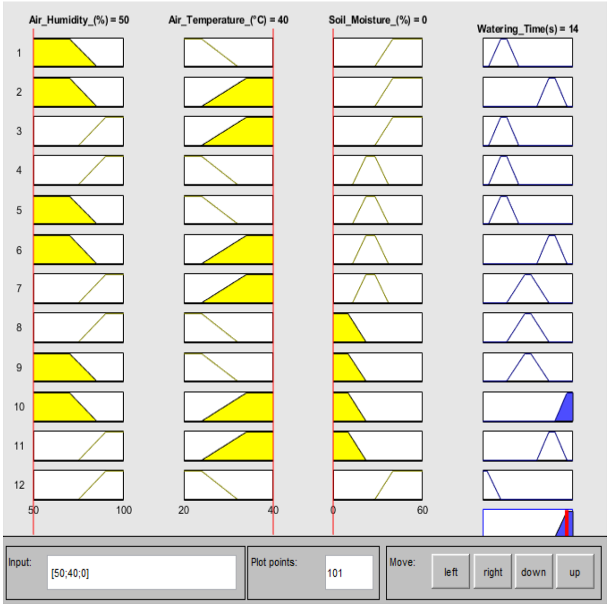

FIGURE 20. Rule viewer about maximum watering time.

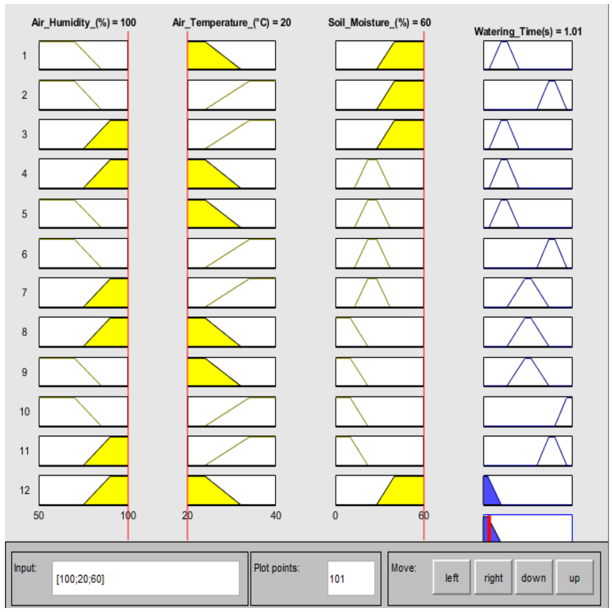

FIGURE 21. Rule viewer about minimum watering time.

The rule viewers presented in Fig. 13, Fig. 14, and Fig. 15 show the simulated watering time output of the fuzzy system in different settings. The surfaces generated in Fig. 16, Fig. 17 and Fig. 18 are used to analyze the system's performance. The relationship between the input variables and the output variables can be visualized easily. From Fig. 16, the relationship between the air temperature and air humidity and the watering time can be identified. The watering time increases significantly as the air temperature increases and the air humidity is low. The watering time rises slowly when both air temperature and humidity increase. The maximum and minimum watering times are 3.5 s and 12 s, respectively. From Fig. 17, the relationship between the air humidity and soil moisture with the watering time can be seen. The watering time is more affected by the soil moisture than by the air humidity. The watering time ranges from 3.5 s to 11 s without considering the air temperature. From Fig. 18, the relationship between the air temperature and soil moisture with the watering time can be seen. The watering time can achieve a maximum of 14 s.

Air temperature plays a more important role in the changes in the watering time. This is because when the air temperature is low, the watering time increases slightly although the soil moisture decreases significantly. The same system is developed using Arduino IDE and uploaded to the Arduino Nano, which receives the data from the master controller and performs the ON/OFF of the relay. Fig. 19 presents an illustration. The time at which the relay is switched ON is based on the fuzzified output. The actual result shown on the serial monitor is tallied with the simulated resulted using MATLAB. Therefore, the Arduino Nano can perform based on the designed fuzzy system. Based on the end-user's information, the chili plant is watered with 100 ml of water mixed with fertilizer 6 times per day (8.40 am, 9.45 am, 10.45 am, 11.45 am, 2 pm, and 4 pm). The time taken for each watering is 2 min.

From Fig. 19, we see that the flow rate of the pump is 5/6 or 0.833 ml/s. In the chili farm monitoring system, the air temperature, air humidity, and soil moisture of the farm are expected to be updated every 15 minutes. This is adjusted on a regular basis by the farmer. The plant will only be watered based on the data collected, which can justify the amount of the water needed for the plant. The rule viewer for the maximum and minimum watering times is shown in Fig. 20 and 21, respectively.

$$
\begin{aligned}
\text{Flow rate} &= \frac{\text{Total Volume of Water Watered}}{\text{Watering Time}} \\
&= \frac{100ml}{2*60s} = \frac{5}{6}ml/s \\
\text{Minimum Volume of Water Watered} & \text{Flow rate} \\
&*\text{Minimum Watering Time} \\
&= \frac{5}{6}*1.06 = 0.883\ ml
\end{aligned}
$$

It can be concluded that the range of watering time under the handling of the proposed fuzzy controller is 3.5 s to 14 s. The manual watering time is 1minute to 2 minutes. The time spent has been reduced significantly about 88.3%. With the proposed system, the farmer can save more time and energy.

Although the soil moisture level is wet, the air humidity is high, and the air temperature is low, the pump will still supply 0.883 ml of water to the plant. However, this volume is very small and can be neglected. In conclusion, the volume of water given to the plant ranges from 0.883 ml to 11.67 ml each time the data are updated. With this analysis, the farmer is able to measure and set the watering volumes efficiently.

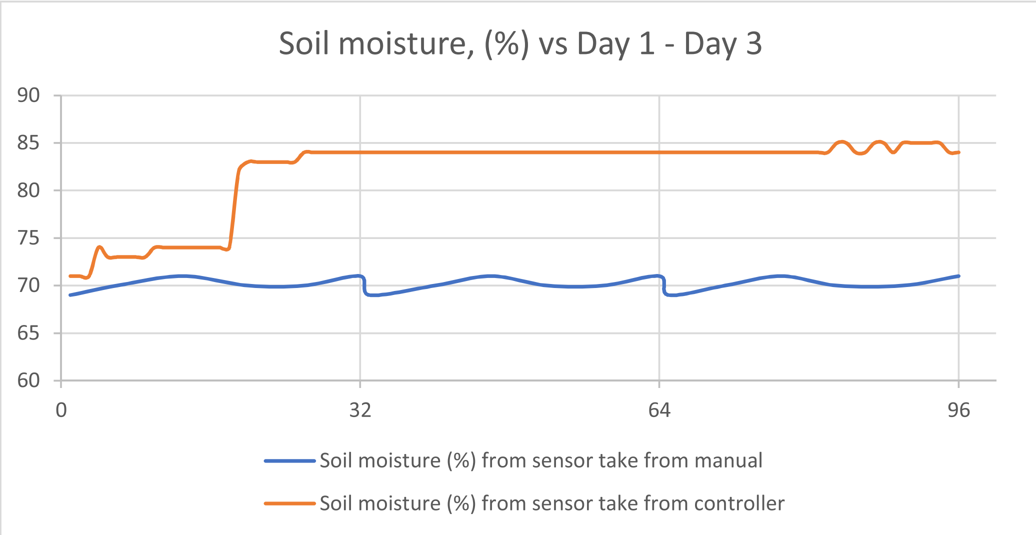

FIGURE 22. Soil moisture (%) vs Number of reading per day.

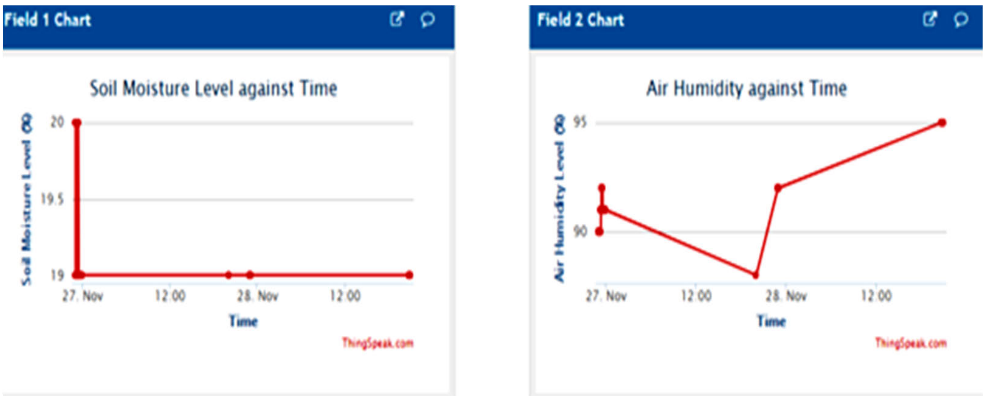

FIGURE 23. The windows from ThingSpeak.com displaying field chart related to soil moisture, and air humidity against time.

Table 4 shows the comparison of watering consumption between manual and fuzzy control. Formula to identify the efficiency of water consumption:

$$\frac{\text{Manual consumption - Fuzzy control consumption}}{\text{Manual consumption}} \times 100\%$$

$$\frac{600 - 373.44}{600} x100\% = 37.76\%$$

By considering the maximum volume of fuzzy control, the watering consumption was able to reduce with 37.76% efficiency.

In relation to water consumption, the percentage of soil moisture will be recorded as well. Figure 22 shows the soil moisture in percentage versus the number of readings taken for 3 days. The reading will be collected from the moisture sensor before each watering routine. For manual reading, it will be taken 6 readings for each day. Thus, the total is 18 readings. For the fuzzy smart controller, the data will be updated by the controller every 15 minutes in 8 hours. Thus, the total is 96 readings which is 32 readings per day. In Figure 22, we tried to overlap both data based on the day taken so that the observation will be easier. For manual reading, the percentage of soil moisture is between 69% to 71%. Even though the percentage is acceptable, but it remains at the minimum value of optimum reading. On the other side, readings from the fuzzy controller are between 71%

TABLE 4. Comparison of manual and fuzzy control watering routine.

Manual watering	Fuzzy control watering
6 times within 8 hours on the day	Every 15 minutes update in 8 hours on the day
100 ml on each schedule	0.833ml to 11.67 ml based on the fuzzy controller setting due to flow rate information
Total water consumption for watering routine: 6 x 100ml = 600ml	Total water consumption for watering routine: 1 hour = 4 updates 8 hour = 32 updates Minimum consumption: 32 x 0.833ml = 26.656ml Maximum consumption: 32 x 11.67ml = 373.44ml

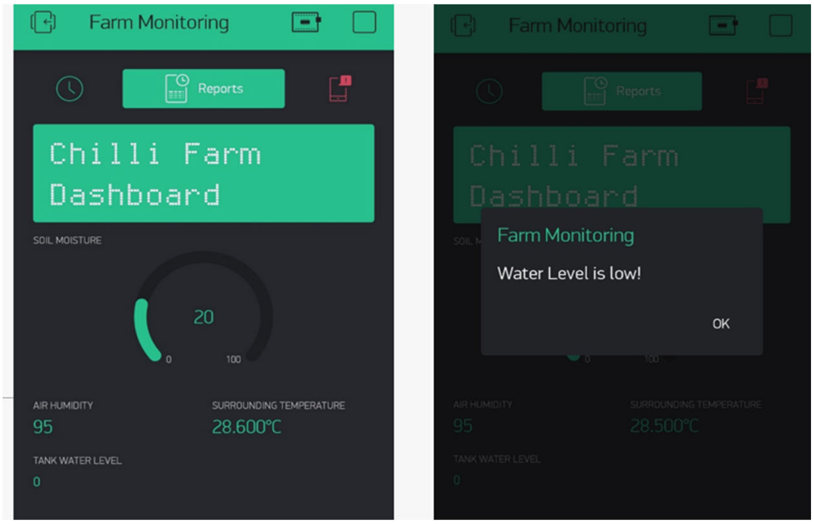

FIGURE 24. Information displayed from Blynk application.

to 84%.it shows that the condition of soil moisture under the handling of the fuzzy controller is precise and much reliable for a sustainable farm. Figure 23 shows two windows from ThingSpeak.com displaying field charts related to soil moisture and air humidity against time. Figure 24 shows the information displayed from the Blynk application. These applications used to be the interface for IoT and the user. From this information, the user will be acknowledged the condition at the farm, able to monitor and react accordingly.

V. CONCLUSION

Agricultural monitoring is needed to reduce the need for human intervention in farming. This demonstrates the advantage of building the rules with mathematical equations and linguistic variables. This process is aimed to educate the farmer on the use of an integrated technology system to monitor and control operations. The system can also create an excellent set of decision-makers with reduced manual contribution. Furthermore, the outcomes help us to understand more about the significance of each variable to obtain healthy plants. This achievement leads to a smart water management. After all, none of the previous studies investigated the chili plant. Chili plants grown in containers have specific needs [27] and can perform exceptionally well given the right conditions. For example, the seeds need more warmth to germinate, and the plants benefit from drier soil in-between watering.

However, there are still a few issues that need to be addressed. First, smart farms can optimize the production outcomes by improving the application of nutrients to the soil and reducing the amount of pesticides and water used in irrigation. These are currently major challenges for the system. The second issue is maintaining the connectivity with the final output, whereby the application layer involves the IoT and provides management information to farmers.For future enhancement, we would like to attain more data so that we can run training and testing of the data. We will also validate the data with different subset. The fuzzy systems itself will be adjusted to be applicable for all types of crops. Different kinds of sensors such as pH sensors, carbon dioxide sensors, and light sensors should be installed to have more reference data to be stored for data storage and analysis.

REFERENCES

[1] K. Jha, A. Doshi, P. Patel, and M. Shah, "A comprehensive review on automation in agriculture using artificial intelligence," *Artif. Intell. Agricult.*, vol. 2, pp. 1–12, Jun. 2019.
[2] V. Saiz-Rubio and F. Rovira-Más, "From smart farming towards agriculture 5.0: A review on crop data management," *Agronomy*, vol. 10, no. 2, p. 207, Feb. 2020.
[3] I. A. Lakhiar, G. Jianmin, T. N. Syed, F. A. Chandio, N. A. Buttar, and W. A. Qureshi, "Monitoring and control systems in agriculture using intelligent sensor techniques: A review of the aeroponic system," *J. Sensors*, vol. 2018, Dec. 2018, Art. no. 8672769.
[4] V. Tilva, J. Patel, and C. Bhatt, "Weather based plant diseases forecasting using fuzzy logic," in *Proc. Nirma Univ. Int. Conf. Eng. (NUiCONE)*, Nov. 2013, pp. 1–5.
[5] A. Gupta, S. Mishra, N. Bokde, and K. Kulat, "Need of smart water systems in India," *Int. J. Appl. Eng. Res.*, vol. 11, no. 4, pp. 2216–2223, 2016.
[6] N. Badariah Ahmad Mustafa, S. Khaleel Ahmed, Z. Ali, W. Bing Yit, A. Azwin Zainul Abidin, and Z. Abidin Md Sharrif, "Agricultural produce sorting and grading using support vector machines and fuzzy logic," in *Proc. IEEE Int. Conf. Signal Image Process. Appl.*, 2009, pp. 391–396.
[7] P. Roseline, C. J. M Tauro, and N. Ganesan, "Design and development of fuzzy expert system for integrated disease management in finger millets," *Int. J. Comput. Appl.*, vol. 56, no. 1, pp. 31–36, Oct. 2012.
[8] H. Webber, T. Gaiser, R. Oomen, and E. Teixeira, "Uncertainty in future irrigation water demand and risk of crop failure for maize in Europe," *Environ. Res. Lett.*, vol. 11, no. 7, 2016, Art. no. 074007.
[9] E. Neamatollahi, J. Vafabakhshi, M. R. Jahansuz, and F. Sharifzadeh, "Agricultural optimal cropping pattern determination based on fuzzy system," *Fuzzy Inf. Eng.*, vol. 9, no. 4, pp. 479–491, Dec. 2017.
[10] Y. Si, G. Liu, J. Lin, Q. Lv, and F. Juan, "Design of control system of laser leveling machine based on fussy control theory," in *Proc. Int. Conf. Comput. Comput. Technol. Agricult.*, 2007, pp. 1121–1127.
[11] S. S. Sannakki, V. S. Rajpurohit, V. B. Nargund, and A. Kumar, "Leaf disease grading by machine vision and fuzzy logic," *Int. J. Comput. Technol. Appl.*, vol. 2, no. 5, pp. 1709–1716, 2011.

[12] M. Valdés-Vela, I. Abrisqueta, W. Conejero, J. Vera, and M. C. Ruiz-Sánchez, "Soft computing applied to stem water potential estimation: A fuzzy rule based approach," *Comput. Electron. Agricult.*, vol. 115, pp. 150–160, Jul. 2015.
[13] A. Kumar, B. Sah, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "A review of multi criteria decision making (MCDM) towards sustainable renewable energy development," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 596–609, Mar. 2017.
[14] E. Giusti and S. Marsili-Libelli, "A fuzzy decision support system for irrigation and water conservation in agriculture," *Environ. Model. Softw.*, vol. 63, pp. 73–86, Jan. 2015.
[15] C.-C. Yang, S. O. Prasher, J.-A. Landry, and H. S. Ramaswamy, "Development of an image processing system and a fuzzy algorithm for site-specific herbicide applications," *Precis. Agricult.*, vol. 4, no. 1, pp. 5–18, Mar. 2003.
[16] Q. Zhengjun, T. Xiaoxing, and S. Jiehui, "Irrigation decision-making system based on the fuzzy-control theory and virtual instrument," *Trans. Chin. Soc. Agricult. Eng.*, vol. 23, no. 8, pp. 165–169, 2007.
[17] V. Khatri, "Application of Fuzzy logic in water irrigation system," *Int. Res. J. Eng. Technol. (IRJET)*, vol. 5, no. 4, p. 3372, 2018.
[18] S. M. Upadhya and S. Mathew, "Implementation of fuzzy logic in estimating yield of a vegetable crop," in *Proc. J. Phys., Conf.*, vol. 1427, Jan. 2020, Art. no. 012013.
[19] T. Asao, *Hydroponics–A Standard Methodology for Plant Biological Researches*. Rijeka, Croatia: InTech, 2012.
[20] A. Barriuso, G. Villarrubia González, J. De Paz, Á. Lozano, and J. Bajo, "Combination of multi-agent systems and wireless sensor networks for the monitoring of cattle," *Sensors*, vol. 18, no. 2, p. 108, Jan. 2018.
[21] B. Basnet and J. Bang, "The State-of-the-Art of knowledge-intensive agriculture: A review on applied sensing systems and data analytics," *J. Sensors*, vol. 2018, Sep. 2018, Art. no. 3528296.
[22] M. O. Akbar, M. J. Ali, A. Hussain, and G. Qaiser, "IoT for development of smart dairy farming," *J. Food Qual.*, vol. 2020, May 2020, Art. no. 4242805, doi: 10.1155/2020/4242805.
[23] M. Ayaz, M. Ammad-Uddin, Z. Sharif, A. Mansour, and E.-H.-M. Aggoune, "Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk," *IEEE Access*, vol. 7, pp. 129551–129583, 2019.
[24] E. Navarro, N. Costa, and A. Pereira, "A systematic review of IoT solutions for smart farming," *Sensors*, vol. 20, no. 15, p. 4231, Jul. 2020, doi: 10.3390/s20154231.
[25] H. N. Surantha, "Smart hydroculture control system based on IoT and fuzzy logic," *Int. J. Innov. Comput., Inf. Control*, vol. 16, no. 1, pp. 207–221, Feb. 2020.
[26] R. S. Krishnan, E. G. Julie, Y. H. Robinson, S. Raja, R. Kumar, P. H. Thong, and L. H. Son, "Fuzzy logic based smart irrigation system using Internet of Things," *J. Cleaner Prod.*, vol. 252, Apr. 2020, Art. no. 119902.
[27] Accessed: Sep. 10, 2020. [Online]. Available: https://verticalveg.org.uk/how-to-grow-chillies-in- containers/

NORAMALINA ABDULLAH (Member, IEEE) received the bachelor's degree in industrial technology from Universiti Sains Malaysia, and the master's degree in automation and mechatronic from Universiti Teknologi Malaysia, and the Ph.D. degree in philosophy from Chulalongkorn University, Bangkok, Thailand, in 2017. Her thesis in Ph.D. was about identification of fault at power transmission line. Her research interests include pertinent to power systems, fault identification, and artificial intelligent. She is currently a member of IEEE and actively contributes in their activities.

NOOR AERINA BINTI DURANI received the bachelor's degree in electronics engineering from Universiti Sains Malaysia. She is actively involved in IEEE Student Branch activities and gained a lot of experience as a student.

MOHAMAD FARID BIN SHARI received the bachelor's degree in electrical engineering from Universiti Sains Malaysia. He is actively involved in IEEE Student Branch activities and gained a lot of experience as a student.

KING SOON SIONG received the bachelor's degree in mechatronics engineering from Universiti Sains Malaysia. He is actively involved in IEEE Student Branch activities and gained a lot of experience as a student.

VICKY KONG WEI HAU received the bachelor's degree in mechatronics engineering from Universiti Sains Malaysia. He is actively involved in IEEE Student Branch activities and gained a lot of experience as a student.

WONG NGEI SIONG received the bachelor's degree in electronics engineering from Universiti Sains Malaysia. He is actively involved in IEEE Student Branch activities and gained a lot of experience as a student.

IR KHAIRUL AZMAN AHMAD (Senior Member, IEEE) received the master's degree in electrical engineering from Universiti Teknologi Malaysia, in October 2009. He is currently a Lecturer with the Faculty of Electrical, Universiti Teknologi MARA, Malaysia. His research interests include piezoelectric ultrasonic devices, piezoelectric energy harvesting in device development and simulation, and characterization of flexible electronic devices.