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Durio Zibethinus L Plantation Intelligent Web-Based Irrigation System using Fuzzy Logic (DuWIMS) Based on IoT

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ABSTRACT

In response to the challenges posed by the recent pandemic on traditional farming in Malaysia, this paper proposes DuWIMS, an innovative smart irrigation system that integrates a modern web interface with an IoT-based system. Utilizing an array of sensors for real-time data collection, the system enhances irrigation efficiency through a dual-mode operation: manual remote control and automated irrigation via a fuzzy logic model. This system, tested on a durian farm in Kedah, Malaysia, significantly reduced irrigation time from two hours to approximately 50 minutes for 65 trees and decreased water usage by about 25%. Furthermore, durian trees irrigated with this system exhibited improved growth compared to those under traditional irrigation methods. Operational efficiency was bolstered with remote irrigation control and reliable performance, as evidenced by no system downtime over a three-month period. The deployment of the fuzzy logic model on a cloud server, serving as a backend API, also proved cost-effective by negating the need for on-site computing units. These findings underscore the potential of DuWIMS to revolutionize agricultural practices, particularly in challenging times, by optimizing resource usage and promoting sustainable farming.

1. Introduction

Food security was a trending topic in Malaysia for many years. Food security is important as it shows that all people in Malaysia have enough food to eat [1]. Recent pandemic of Covid-19 had caused a major problem for Malaysia's food security. The problem faced by Malaysia is not in terms of individual health nutrition, but economic development. When the Covid-19 pandemic hit Malaysia, plantation export hit an all-time low. Malaysia's major plantations like palm oil and durian had a reduction in total export due to the lockdown. Malaysia's plantation industry relies on manual workers. When the lockdowns happen during the pandemic, the plantation work had to be halted. According to Malaysia research in 2019, Malaysia plantations lay off a lot of their workers due to

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MCO rules like the lockdown which prevent the worker to travel to the field to carry out their work. [2] Sabah is one of the largest palm-oil plantations producing states, had its plantation activity stops in six districts. This caused a heavy impact on Malaysia's economy, where Malaysia suffers a 20% export output loss [3]. Based on the research on Malaysian Labor, during the pandemic, Malaysia was short of 500,000 jobs for the agriculture sector. This caused the production of plantations to drop. Malaysia's palm oil production lost roughly seven hundred thousand tons of product in the year 2020. This greatly affects Malaysia's food security status as the economy plummeted [4]. As Covid-19 got controlled and Malaysia's economy started to recover, it exposed 2 major problems that the traditional way of the plantation was facing.

The traditional way of plantation consists of manual activity irrigation, fertilization, and more. This activity usually requires human labour which starts with farmers going to their plantation site. The farm activity includes monitoring, irrigation, fertilization, soil preparation, and yield collection. Most of the farming time (70%) will be used for monitoring and irrigation [5]. Every plantation needs different water levels, temperatures, and soil conditions to obtain its optimum yield. Hence, specific monitoring had to be carried out at the plantation site to obtain optimal yield production [6]. The traditional way of monitoring and irrigation was carried out where farmers had to go to their plantation site to manually record their plantation status and decide whether it is suitable to water those plantations. As the Covid-19 pandemic started, farmers were unable to travel to their plantation sites due to the lockdown rules. This caused 70% of the farming activity to be halted, thus reducing yield production. Without proper monitoring and an irrigation system, the plantation is unable to produce healthy crops with an optimum yield. Furthermore, the irrigation level that was determined from the monitoring activity suffers from human error. The farmer had to manually record the characteristics data of each plantation in a large area. This data was vulnerable to error as the recording is carried out gradually throughout the plantation site. This problem shows that the traditional way of farming not only was costly as it relied on manual labour work, but it also suffered from inconsistent and deferred data.

Recent growth in technology, especially on the Internet of Things (IoT) sector has helped the traditional way of farming to solve its problems. IoT has grown over the years and affected a wide range of applications branching from manufacturing, health, communication, and agriculture [7]. IoT can be defined as a network that connects physical devices like sensors and actuators with the internet allowing the devices to communicate with each other, exchange data, and process the data [8]. In agriculture sectors, various sensors would be used to detect and record the unique data of plantations. This data will be a further process depending on the application. IoT also reduces manual labour, as the IoT nodes record and send data automatically. Thus, farmers do not have to travel physically and regularly to the plantation site to carry out their farming activity. Moreover, all the detected plantation data will be transmitted in real-time, hence solving the inconsistent and deferred data of the traditional farming method. There is various research regarding the IoT application in agriculture sectors. As the most important activity for farming is irrigation, an IoT-automated irrigation system would help improve plantation productivity.

Recent researchers have designed different irrigation systems featuring different sensors and network setups. Krishnan *et al.,* [9] designed a smart agriculture system featuring an irrigation control system. The system contains an Arduino controller, GSM, motor, soil moisture sensor, temperature sensor, and humidity sensor. The sensors connected to the Arduino controller will detect their respective data and transmit it to a coordinator node using GSM. The coordinator node will then upload the data to the web server and display it in the Android application. The system will turn on the irrigation valve based on the fuzzy logic controller output. A fuzzy logic system is deployed on a controller to compute the sensor input data and determine the motor status. The proposed system was able to reduce the time needed for irrigation by 7% when compared to the manual irrigation system. Although the system proposed by Krishnan *et al.,* [9] did enhance the traditional irrigation system, it has stability issues as the irrigation output depends on the fuzzy logic controller deployed on site. A Smart Irrigation system proposed by Keswani B utilizes a different approach compared to the previous irrigation system [10]. The proposed system combines IOT wireless sensor network with a neural network. The neural network will be used to predict soil moisture content based on the farm history. The soil moisture content data, sensor data, and weather data will be entered into fuzzy logic modelling system. The fuzzy logic model will command the valve status based on the input data. The proposed system was able to water the plantation under different weather conditions. Based on the proposed irrigation system, the system solved the fuzzy logic system problem of the previous irrigation system as the computing unit was a computer. The data collected will be stored in a server, and the computing computer will access the data and process it using the fuzzy logic model and produce the valve command output. It still has the same weakness as the previous irrigation system as the user had no control over the irrigation system.

Hassan et *al.,* proposed a smart irrigation system with a photovoltaic supply [11]. This proposed system carries similar features to the previous research's system. Multiple sensors like light, temperature, humidity, soil moisture, and water flow sensor were connected to a microcontroller. The unique feature that this proposed system had is the PWM solar charge controller that charges the battery for the microcontroller. The PWM solar charge controller controlled the input voltage received by the solar panel. The proposed system was able to prolong the battery life of the controller, with the battery holding off for 3 days without charging. Recent research on smart irrigation system from the year 2019 to 2022 [9-11], shows that IoT smart irrigation system was able to replace traditional irrigation system. All the previous proposed system had their unique features but still faced the same problem. The previously proposed system was missing a proper web system that allows farmers to interact with the irrigation system. Thus, we proposed to develop a modern irrigation system that had both monitoring and control mechanisms displayed and usable on a web system and a fuzzy logic computing system on a cloud server.

The main purpose of this study is to develop an intelligent irrigation system containing both monitoring and control mechanisms. The proposed irrigation system combined both web system and irrigation system. The proposed system implements fuzzy logic system that interact with the web system. Multiple sensors were used to collect data from the farm, and these data were used in the fuzzy model. The fuzzy model will compute the volume of irrigation and time needed for irrigation. The proposed system would also reduce manual labour during irrigation process by allowing user to remotely control the water valve through the web system. This helps to reduce the needs of manual labour during irrigation process. Through the precise computed volume of irrigation and time needed for irrigation, the proposed system could reduce irrigation time and water consumption.

2. Methodology

The proposed system features two main parts. The first part is the web system while the second part is the irrigation mechanism. The web system could display real-time sensor data in graphs, providing real-time irrigation control, and managing plantation information. The real-time sensor data will allow the farmer to monitor their farm condition from their residence. The real-time irrigation mechanism let farmer control the irrigation valve straight from the web instead of traveling to their plantation field to stop the water pump for irrigation. Furthermore, the system also labels each of the plantations on the plantation site. This allows farmers to update information regarding the individual plantation and monitor its growth condition. The architecture of the web system was shown in Figure 1.

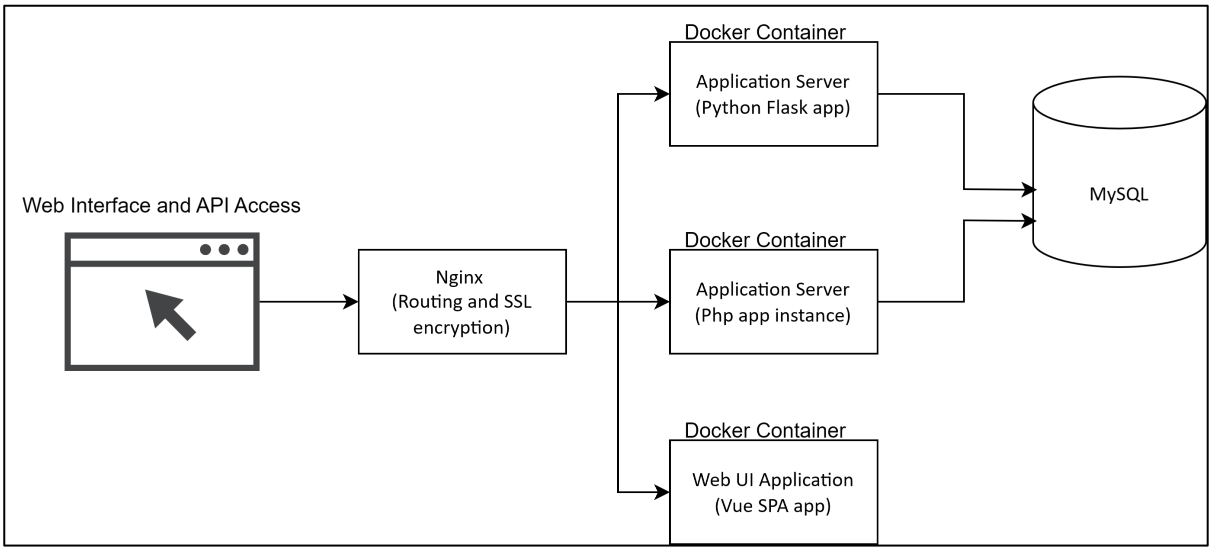


Fig. 1. Web system Architecture

2.1 Web System

The web system was separated into two main parts, the frontend part, and the backend part. The web system was deployed on a docker container which served in a webserver. Docker container is a standalone package of software that runs on docker [12]. Docker isolates the application from the underlying operating environment, which enhances the performance of the application. Both the frontend part and backend part of the web system was deployed in a different docker container. The frontend part was developed with the Vue JavaScript framework. It was deployed as a docker container which served as the web UI application. The user will access the front end of the web system with a webpage routed by the Nginx web server. Nginx is a web server that routes all the HTTP requests by the user to the correct container. The Nginx web server used in the system was configured with Secure Sockets Layer (SSL) protection. SSL protects the network from an active, man-in-middle attacker, which ensures the communication between client and server was guaranteed to be secure [13]. The backend part of the web system contains two different application servers running on their docker container. The first application server will handle all the browser APIs that access the MYSQL database. This server was running with a PHP server script. It also handles the request from the sensor node for the irrigation system on both monitoring and irrigation control mechanisms. The second application server was running on the FLASK server. This server holds the fuzzy logic model. As the fuzzy logic model was running on a server, it allows real-time processing. Both application servers will access the same database. The database used here was the MYSQL database.

2.2 Irrigation System

The irrigation part contains both monitoring and controlling mechanisms. The system has two major units: the sensor node and the control node. The sensor node contains the ESP32 controller, WIFI module, humidity sensor, light sensor, soil moisture sensor, soil temperature sensor, and ambient temperature sensor. The control node contains an ESP32 controller, WIFI module, ultrasonic sensor, water flow sensor, soil moisture sensor, soil temperature sensor, and electronic water valve. The sensor device node handles the monitoring mechanism. The block diagram of the irrigation system is demonstrated in Figure 2.

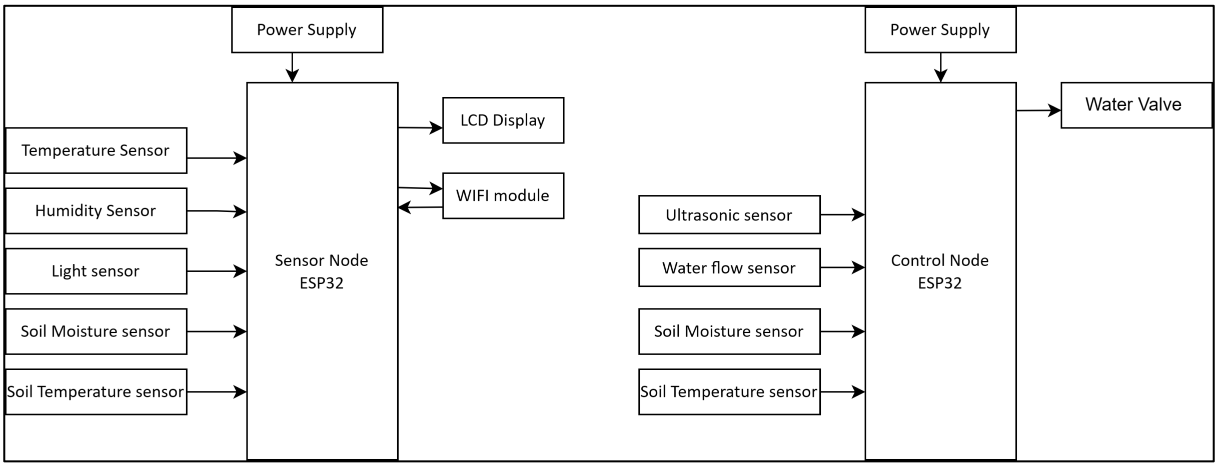


Fig. 2. Block diagram of proposed irrigation system

Multiple sensors re connected to the ESP32 controller. The controller collects the sensor data and uploads it into the database through a WIFI connection. The ESP32 uploads sensor data to the database by using the API provided by the PHP application server. The sensor data stored in the database will be accessed by the Web UI application, thus providing real-time monitoring of plantation parameters. The Web UI application can be viewed in a browser on every platform. The control node handles the irrigation mechanism. An ESP32 controller was connected to the electronic water valve. The controller will receive instructions from the Application server to switch on or off the water valve. The water flow sensor was also connected to the controller. This sensor will detect the water flow rate. The controller will generate the total water volume of water flow based on the water flow rate. The soil moisture sensor and soil temperature sensor will record the soil condition when the water valve was operating. The last sensor connected to the controller was the ultrasonic sensor. This sensor was used to measure the water tank volume. Both nodes were powered by solar energy. A solar panel was connected to a charging controller which generate 12V. The 12V was further stepped down to 5V by using a regulator connected to the ESP32 controller. Figure 3 shows the block diagram of the solar panel connection.

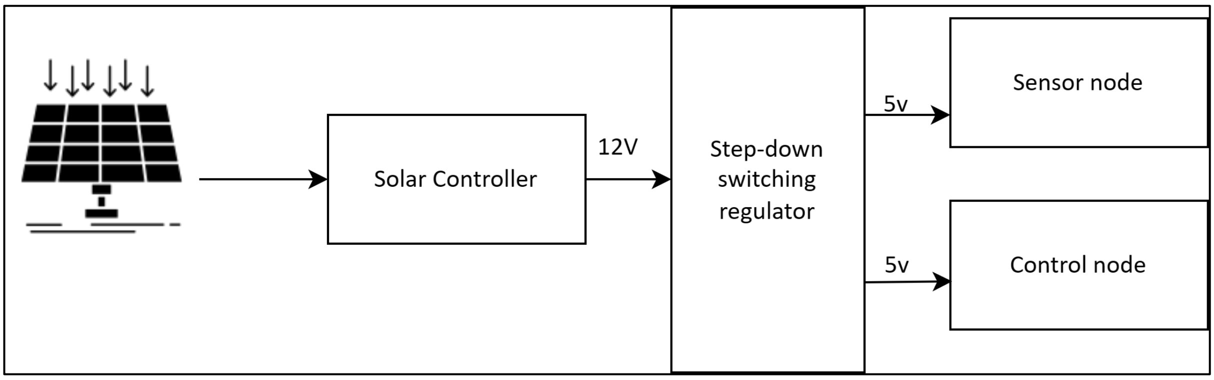


Fig. 3. Solar panel connection

2.3 Working Principle

The system works as per the flowchart given in Figure 4 and it involves the following steps.

1. Admin register sensor node and controller node in the web system.
2. A one-time setup sensor node that initializes the sensor node to start sending data to the database.
3. Continuous data sensing and uploading data into the database.
4. The web system fetches data from the database to display on the dashboard.
5. The user manually controls irrigation or selects the fuzzy logic auto mode.
6. The control node opens or closes the water valve based on the decision data.

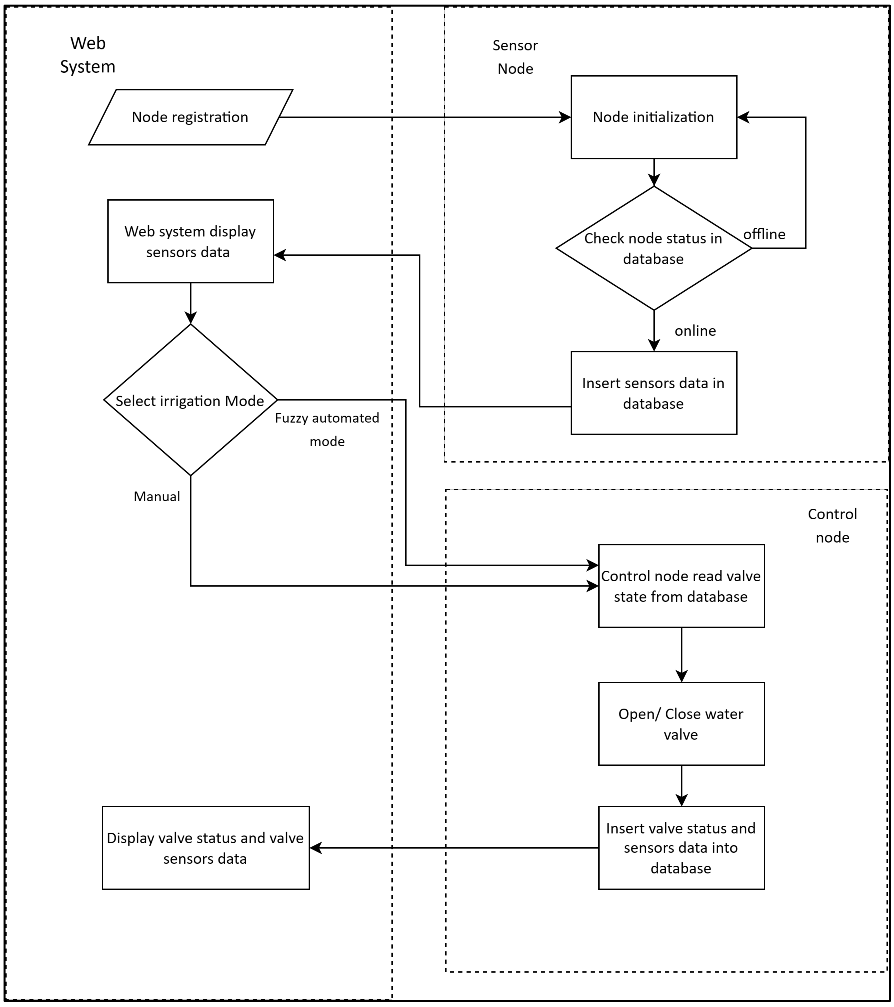


Fig. 4. Workflow of the proposed system

As shown in the flowchart, the system starts with registering the sensor node and control node in the web system. The sensor node and control node represent the area they were placed in. Once registered, the sensor node will initialize and upload test data into the database. Once the web system receives the test data from the sensor node, the sensor node will be confirmed to be online in the web system. The sensor node will start to collect sensor data and upload it into the database, while the web system will fetch the data from the database and display it in the dashboard. The web system will have a section that shows the irrigation control panel. By accessing this panel, farmers will be able to remotely control the water valve, either through manual control or using the fuzzy logic system to automate the irrigation control. Once the farmer changes the valve state to ON or OFF, the web system will record the valve condition in the database. The control node will read the newest valve status in the database. Based on the valve status, the controller will switch on or off the water valve. When the water valve was triggered, the controller will initiate sensors to start sensing data and insert the valve status, sensor data, date, and time into the database. The web system will display the data transmitted by the controller node including the valve status and the soil moisture, and temperature value. This allows users to know the condition of their plantation site while irrigation is running in real-time. Furthermore, users could also use the fuzzy logic system to automate irrigation control.

2.4 Fuzzy Logic System

The fuzzy logic system had been used in different systems such as remote sensing systems [14] and control systems. The fuzzy logic system was primarily used in the decision-making stage of a system. It contained 3 different stages which were fuzzification, interference, and defuzzification [15]. The fuzzy logic system that was implemented in this project was shown in Figure 5. A fuzzy logic system starts with fuzzification where it takes in input variable and converts it into linguistic values that represent the fuzzy sets. Next, a knowledge base will be built based on farmer knowledge of the farming domain. The knowledge base contains membership functions and fuzzy rules. The membership functions make up the definitions that define the input variable. The fuzzy rule was used to define the control goals and policy of the output. Both membership functions and fuzzy rules were built with the data from farmers. Defuzzification was performed last to map the range of values of output into quantitative information. The input used in the proposed system were ambient temperature, humidity percentage, soil temperature, soil moisture, and light intensity. The system will compute the output for irrigation which contains the irrigation level, volume of irrigation, and time needed to finish the irrigation.

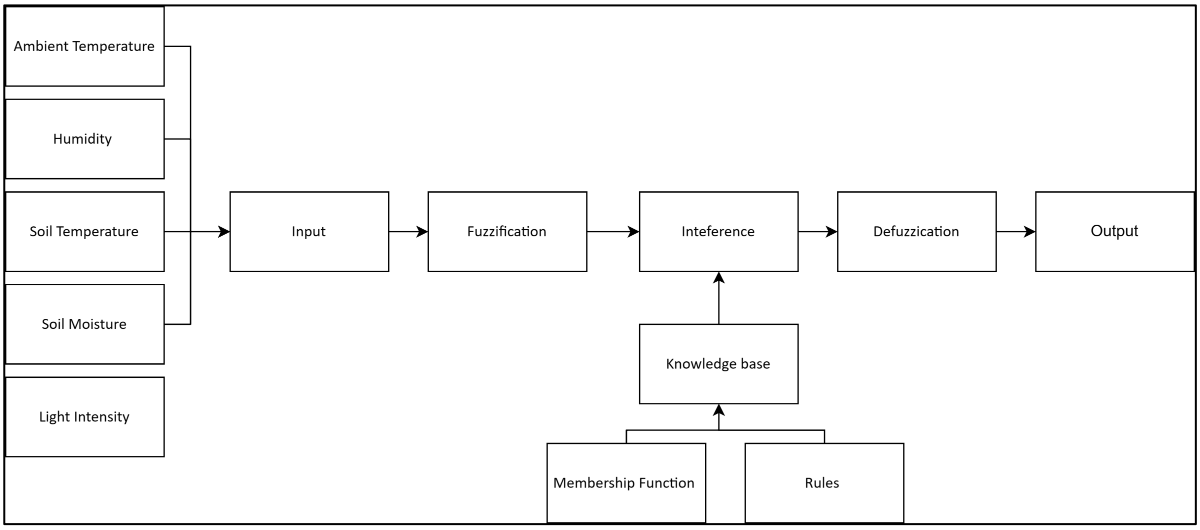


Fig. 5. Fuzzy Logic System

Ambient temperature affects the efficiency of irrigation, as the high temperature required more water to be used in irrigation. Thus, a temperature sensor was used to collect ambient temperature data. Figure 6 shows the membership functions of the ambient temperature. As Malaysia's temperature varies between lower 20°C to upper 40°C, thus we classified the temperature into 4 categories. The very low section of temperature rarely happens in Malaysia, as Malaysia is a tropical country. The mean ambient temperature in Malaysia varies from 28°C to 30°C [16], hence the medium class of the temperature was in between the mean temperature of Malaysia. The membership function equation was represented below.

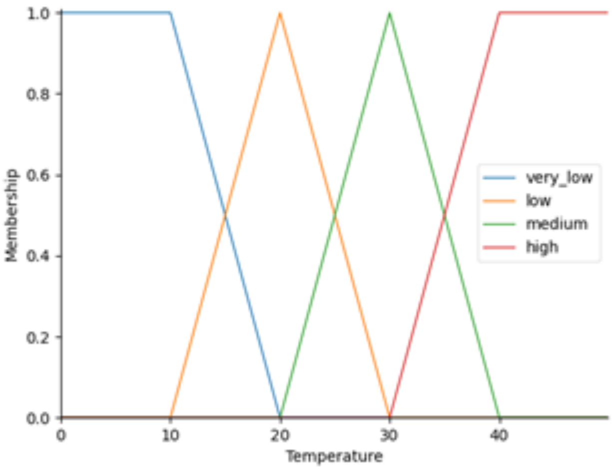


Fig. 6. Ambient temperature membership function

$$Temp_{\boldsymbol{very}\ low}(x) = \begin{cases} 1, x \le 10 \\ \frac{20-x}{10}, 10 < x \le 20 \end{cases} \tag{1}$$

$$Temp_{low}(x) = \begin{cases} 0, x \le 10 \\ \frac{x-10}{10}, 10 \le x \le 20 \\ \frac{30-x}{10}, 20 \le x \le 30 \\ 0,30 \le x \end{cases} \tag{2}$$

$$Temp_{low}(x) = \begin{cases} 0, x \le 10 \\ \frac{x-10}{10}, 10 \le x \le 20 \\ \frac{30-x}{10}, 20 \le x \le 30 \\ 0,30 \le x \end{cases} \tag{3}$$

$$Temp_{high}(x) = \begin{cases} \frac{x-30}{10}, 30 \le x \le 40 \\ 1,40 \le x \end{cases} \tag{4}$$

The next input parameter for the fuzzy system is the soil temperature. Soil temperature is one of the major parameters that affect the growth of plantations. Based on Frey's research on soil temperature response [17], the soil temperature was affecting the microorganism in the soil which affects the growth of the plantation. The research revealed that the optimum soil temperature for plant growth was 10°C to 25°C, as the microorganism in the soil were more active. The research was carried out in different countries and compared to Malaysia; Malaysia had a higher ambient temperature. Hence, the soil temperature used in the system was separated into 4 categories. The optimum soil temperature was increased by 10°C, thus resulting in between 20°C to 35°C. Figure 7 shows the membership function for soil temperature. The membership function equation was represented below.

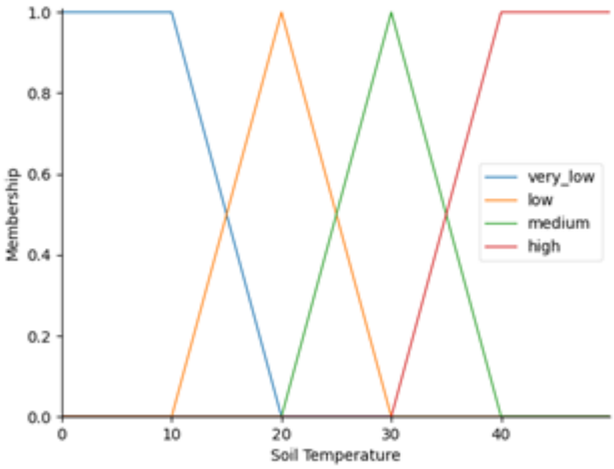


Fig. 7. Soil temperature membership function

$$Soil\ Temp_{very\ low}(x) = \begin{cases} 1, x \leq 10 \\ \frac{20-x}{10}, 10 < x \leq 20 \end{cases} \tag{5}$$

$$Soil\ Temp_{low}(x) = \begin{cases} 0, x \leq 10 \\ \frac{x-10}{10}, 10 \leq x \leq 20 \\ \frac{30-x}{10}, 20 \leq x \leq 30 \\ 0,30 \leq x \end{cases} \tag{6}$$

$$Soil\ Temp_{medium}(x) = \begin{cases} 0, x \leq 20 \\ \frac{\mathrm{x}-20}{10}, 20 \leq x \leq 30 \\ \frac{40-x}{10}, 30 \leq x \leq 40 \\ 0,40 \leq x \end{cases} \tag{7}$$

$$Soil\ Temp_{high}(x) = \begin{cases} \frac{x-30}{10}, 30 \leq x \leq 40 \\ 1,40 \leq x \end{cases} \tag{8}$$

Humidity or ambient humidity was used as an input parameter in the fuzzy system. Humidity or relative humidity often affects soil water repellence. Water repellence of soil prevents water to infiltrate soil [18]. Doerr research on water repellence shows that the soil had high water repellence when the soil was exposed to 98% relative humidity in a brief period [19]. The water vapor from the surrounding was absorbed into the soil, thus increasing the water repellence of the soil. If the relative humidity of the surroundings increased, the soil would sustain its wettability which decreased the chances of water infiltrating into the soil. The humidity percentage was separated into 4 categories, with the highest humidity being more than 70%. Malaysia's average humidity was between 75% to 95 %, hence instead of keeping the highest humidity level at a relative 98%, the highest humidity for the fuzzy system was set at 75 [20]. Figure 8 shows the membership function for soil temperature. The membership function equation was represented below.

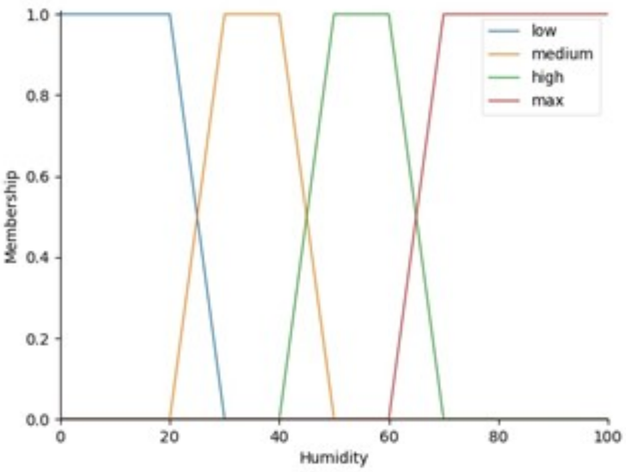


Fig. 8. Humidity membership function

$$Humidity_{low}(x) \quad = \begin{cases} 1, x \leq 20 \\ \frac{30-x}{10}, 20 < x \leq 30 \end{cases} \tag{9}$$

$$Humidity_{medium}(x) = \begin{cases} 0, x \leq 20 \\ \frac{x-20}{10}, 20 \leq x \leq 30 \\ 1, 30 \leq x \leq 40 \\ \frac{50-x}{10}, 40 \leq x \leq 50 \\ 0, 50 \leq x \end{cases} \tag{10}$$

$$\mathrm{Humidity}_{high}(x) \quad = \begin{cases} 0, x \leq 40 \\ \frac{\mathrm{x}-40}{10}, 40 \leq x \leq 50 \\ 1, 50 \leq x \leq 60 \\ \frac{70-x}{10}, 60 \leq x \leq 70 \\ 0, 70 \leq x \end{cases} \tag{11}$$

$$\mathrm{Humidity}_{max}(x) \quad = \begin{cases} \frac{x-60}{10}, 60 \leq x \leq 70 \\ 1, 70 \leq x \end{cases} \tag{12}$$

Soil moisture was also used as an input parameter for the fuzzy system. Soil moisture represents the amount of water content in the soil. It also controls the groundwater storage of soil as it determines the amount of water that infiltrates into the soil [21]. Soil moisture is often affected by soil temperature. Based on Venkat's research on the relationship between soil moisture and temperature, there was a linear relationship between soil moisture and soil temperature [22]. It also states that an increased in ambient temperature and soil temperature would reduce soil moisture [22]. Soil moisture also affects soil evaporation, as low soil moisture caused lesser water to be evaporated. This affects the evapotranspiration of plantations, where their growth was limited by the lack of water, and energy from evaporation [23]. The soil moisture data were measured in percentage, and it was classified into five categories which are very low, low, medium, high and maximum. Relative humidity and ambient temperature affect the soil moisture; hence the optimum soil moisture was assumed to be at between 20% to 90%. Very low soil moisture was set at below

10% as Malaysia's relative humidity was high, it was rare to have soil moisture be dry. Malaysia's ambient temperature was high; hence soil moisture rarely reaches 90% throughout the day. Figure 9 shows the membership function for soil temperature. The membership function equation was represented as below.

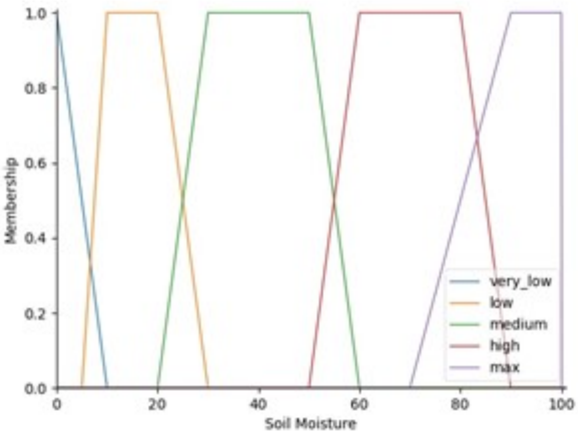


Fig. 9. Soil Moisture membership function

$$SoilMoisture_{very\ low}(x) \quad = \begin{cases} \frac{10-x}{10}, 0 \leq x \leq 10 \\ 0,10 \leq x \end{cases} \tag{13}$$

$$SoilMoisture_{low}(x) \quad = \begin{cases} 0, x \leq 10 \\ \frac{x-5}{5}, 5 \leq x \leq 10 \\ 1,10 \leq x \leq 20 \\ \frac{30-x}{10}, 20 \leq x \leq 30 \\ 0,30 \leq x \end{cases} \tag{14}$$

$$\mathrm{SoilMoisture}_{medium}(x) \quad = \begin{cases} 0, x \leq 20 \\ \frac{\mathrm{x}-20}{10}, 20 \leq x \leq 30 \\ 1,30 \leq x \leq 50 \\ \frac{60-x}{10}, 50 \leq x \leq 60 \\ 0,60 \leq x \end{cases} \tag{15}$$

$$\mathrm{SoilMoisture}_{high}(x) \quad = \begin{cases} 0, x \leq 50 \\ \frac{\mathrm{x}-50}{10}, 50 \leq x \leq 60 \\ 1,60 \leq x \leq 80 \\ \frac{90-x}{10}, 80 \leq x \leq 90 \\ 0,90 \leq x \end{cases} \tag{16}$$

$$\mathrm{SoilMoisture}_{max}(x) \quad = \begin{cases} \frac{x-70}{20}, 70 \leq x \leq 90 \\ 1,90 \leq x \end{cases} \tag{17}$$

The last input parameter was light intensity. Light intensity is the amount of light that is exposed to the plantation. Light intensity affects the transpiration rate of the plant, where the rate of at the plant releases its water vapor depends on the light intensity [24]. The light intensity also scales with the ambient temperature. High light intensity will result in high ambient temperature. Based on the research on coffee arabica leaf at different irrigation and light intensity levels, a plantation that is exposed to a medium light intensity environment and high irrigation level has the highest growth rate [25]. If the plant is exposed to a high light -light-intensity environment, its water evaporation rate would increase. This caused the plant to reduce its photosynthesis rate, which reduce the growth rate of the plant. Malaysia's daily average light intensity reading is in between sixty thousand lux to eighty thousand lux [26]. The light intensity level was classified into three categories, where the medium light intensity was in between forty thousand to sixty thousand lux. High light intensity was in between fifty thousand and hundred thousand lux Figure 10 shows the membership function for light intensity. The membership function equation was represented as below.

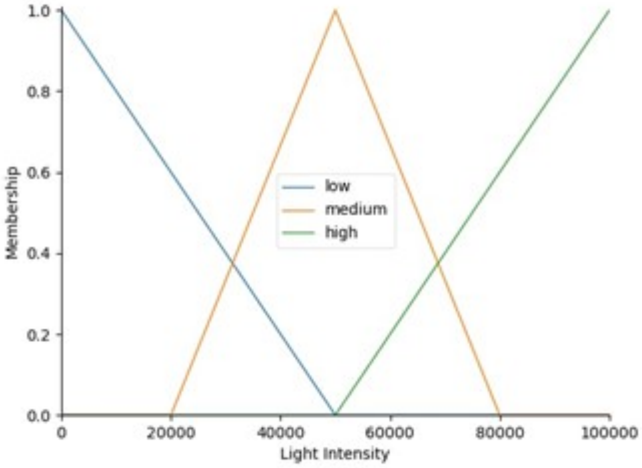


Fig. 10. Light Intensity membership function

$$LightIntensity_{low}(x) = \begin{cases} \frac{50000-x}{50000}, x \leq 50000 \\ 0, 50000 \leq x \end{cases} \quad (18)$$

$$LightIntensity_{medium}(x) = \begin{cases} 0, x \leq 20000 \\ \frac{x-20000}{30000}, 20000 \leq x \leq 50000 \\ \frac{80000-x}{30000}, 50000 \leq x \leq 80000 \\ 0, 80000 \leq x \end{cases} \quad (19)$$

$$\mathrm{LightIntensity}_{high}(x) = \begin{cases} \frac{\mathrm{x}-50000}{50000}, 50000 \leq x \leq 100000 \end{cases} \quad (20)$$

The output of the fuzzy system is the irrigation level. The irrigation level starts from 0 to 100%. Based on the irrigation level output, the backend API will compute the time needed and volume of water needed to fulfil the irrigation level. These outputs will then be displayed at the frontend website. The irrigation was classified into five different categories. Figure 11 shows the membership function for the irrigation level. The membership function equation was represented below.

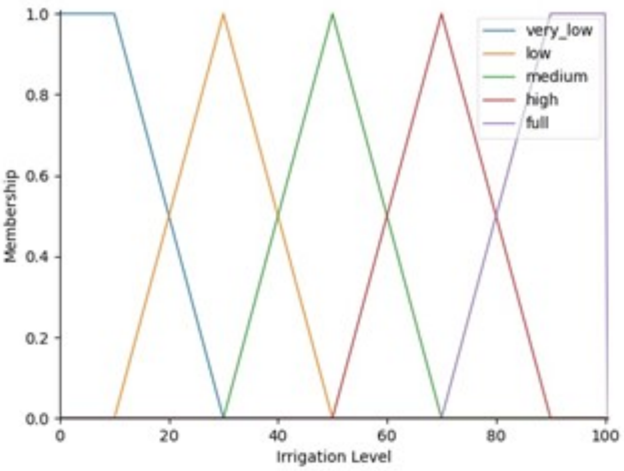


Fig. 11. Irrigation Level membership function

$$IrrigationLevel_{very\ low}(x) = \begin{cases} 1, x \leq 10 \\ \frac{30-x}{20}, 10 < x \leq 30 \end{cases} \tag{21}$$

$$IrrigationLevel_{low}(x) \quad = \begin{cases} 0, x \leq 10 \\ \frac{x-10}{20}, 10 \leq x \leq 30 \\ \frac{50-x}{20}, 30 \leq x \leq 50 \\ 0{,}50 \leq x \end{cases} \tag{22}$$

$$\mathrm{IrrigationLevel}_{medium}(x) = \begin{cases} 0, x \leq 30 \\ \frac{\mathrm{x}-30}{20}, 30 \leq x \leq 50 \\ \frac{70-x}{20} 50 \leq x \leq 70 \\ 0{,}70 \leq x \end{cases} \tag{23}$$

$$\mathrm{IrrigationLevel}_{high}(x) \quad = \begin{cases} 0, x \leq 50 \\ \frac{\mathrm{x}-50}{20}, 50 \leq x \leq 70 \\ \frac{90-x}{20}, 70 \leq x \leq 90 \\ 0{,}90 \leq x \end{cases} \tag{24}$$

$$\mathrm{IrrigationLevel}_{max}(x) \quad = \begin{cases} \frac{x-70}{10}, 70 \leq x \leq 90 \\ 1{,}90 \leq x \end{cases} \tag{25}$$

The output of the fuzzy system was computed using the pre-set fuzzy rules shown in Table 1. The fuzzy rules were determined based on the previous research data and farmer’s data.

Table 1
Fuzzy rules example for proposed fuzzy logic system

Number	Rule
1	If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “Low”) ^ (Soil Moisture is “Low” | “Very Low”) ^ (Light intensity is “Low”), then (irrigation level is “Low”)
2	If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “Medium”) ^ (Soil Moisture is “Medium” | “Low”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”)
3	If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “High”) ^ (Soil Moisture is “High”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”)
4	If (Ambient Temperature is “Very Low”) ^ (Soil Temperature is “Very Low”) ^ (Ambient Humidity is “Maximum”) ^ (Soil Moisture is “Maximum”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”)
5	If (Ambient Temperature is “Low”) ^ (Soil Temperature is “Low”) ^ (Ambient Humidity is “Low”) ^ (Soil Moisture is “Low” | “Very Low”) ^ (Light intensity is “Low”), then (irrigation level is “Medium”)
6	If (Ambient Temperature is “Low”) ^ (Soil Temperature is “Low”) ^ (Ambient Humidity is “Medium”) ^ (Soil Moisture is “Medium”) ^ (Light intensity is “Low”), then (irrigation level is “Low”)
7	If (Ambient Temperature is “Low”) ^ (Soil Temperature is “Low”) ^ (Ambient Humidity is “High”) ^ (Soil Moisture is “High”) ^ (Light intensity is “Low”), then (irrigation level is “Very Low”)
8	If (Ambient Temperature is “Medium”) ^ (Soil Temperature is “Low” | “Medium”) ^ (Ambient Humidity is “Low”) ^ (Soil Moisture is “Low” | “Very Low”) ^ (Light intensity is “Low” | “Medium), then (irrigation level is “High”)
9	If (Ambient Temperature is “Medium”) ^ (Soil Temperature is “Low” | “Medium”) ^ (Ambient Humidity is “Medium”) ^ (Soil Moisture is “Medium” | “Low”) ^ (Light intensity is “Low” | “Medium”), then (irrigation level is “Medium”)
10	If (Ambient Temperature is “Medium”) ^ (Soil Temperature is “Low” | “Medium”) ^ (Ambient Humidity is “High”) ^ (Soil Moisture is “High” | “Medium”) ^ (Light intensity is “Low” | “Medium”), then (irrigation level is “Low”)
…	…

3. Results

The system was implemented in on a real farm located at in Kedah, Malaysia. The farm was managed by TW Megastar. The primary plantation of the farm is the durian tree. The durian plantation is located at Muda Kuari, Tunjang Jitra, Kedah. The total farm area is 2.5 acres. Figure 12 shows the location of the durian farm. The farm currently had planted 65 durian trees. The placement of the tree was mapped in Figure 13.

Fig. 12. TW Megastar Durian Plantation Farm

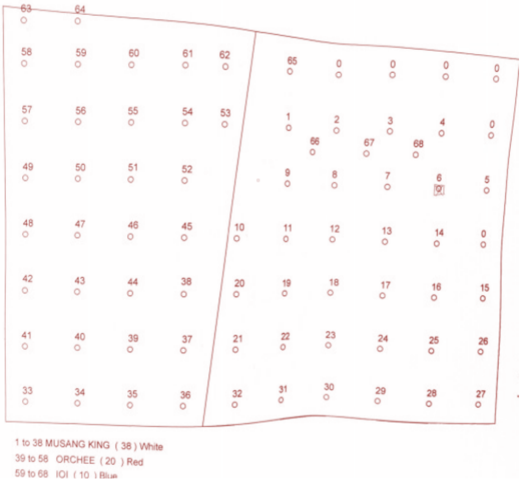


Fig. 13. Durian tree mapping

3.1 Hardware

Based on the mapping of the durian tree, the irrigation system was implemented at the first tree row of the tree. The hardware setup of the irrigation system was like a traditional drip irrigation system where the water pipes were first connected to a water tank. The water pipes were then separated into different drip lines on each row of the durian tree. The control node was implemented at the main pipe that connects to each of the drip lines. It will control the valve connected to each drip line. The sensor node was installed at different sections of the farm. The current setup for the farm was two sensor nodes that were separately installed at the left and right sides of the farm. Figure 14 shows the durian tree plantation with drip piping. Figure 15 shows the irrigation piping at individual trees. The set-up of the control node was shown in Figure 16. Figure 17 shows the sensor node. The control and sensor nodes were ensembled before installing at the farm.

Fig. 14. Drip piping with the durian tree

Fig. 15. Piping at durian tree

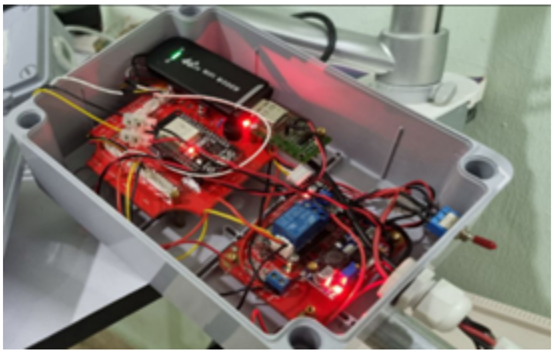


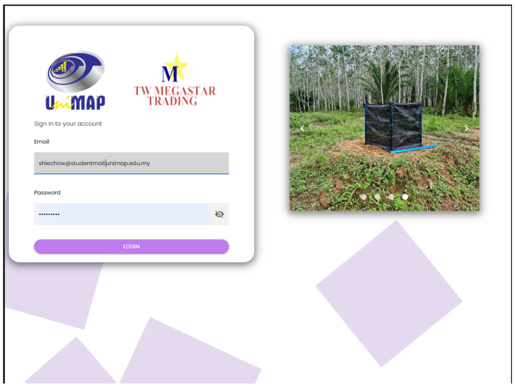
Fig. 16. Control node prototype

Fig. 17. Sensor node prototype

3.2 Web System

The web system was deployed on a cloud server at www.twm.5ir.tech. The web system had zero downtimes since it was deployed. It also didn’t suffer from digital attacks as the web system was encrypted with SSL. The data stored in the web system was well secured. The web system displays the real-time data collected from the sensor node and display in the dashboard form. The data can be viewed in hourly, daily, or monthly form. Data will be fetched from the database every 10 minutes, thus the data shown in the dashboard is always the newest data collected by the sensor node. In the dashboard, the newest data was displayed separately below the header. Each card represents each sensor’s data. The body section of the dashboard had two graphs displaying humidity-ambient temperature data and soil moisture-soil temperature data. The button could switch the graph form based on its view form. The custom and search tab allows customize and query-based data views.

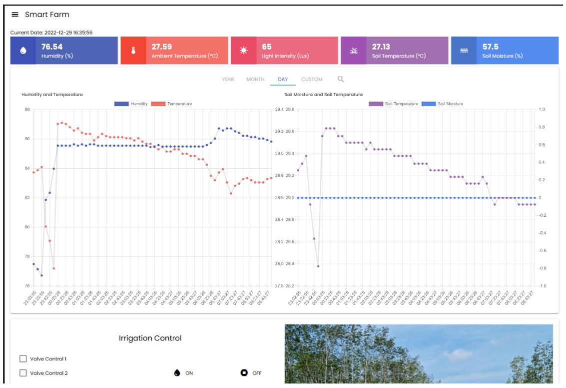
The web system also includes a tree registration system. The tree page shows a collection of planted tree data. It allows the farmer to record individual growth data of the durian tree. Figure 17 shows the login page of the web system. Figure 18 shows the main dashboard of the web system. Figure 19 shows the custom graph and Figure 20 shows the tree details page.



Email: shiechow@studentmail.unimap.edu.my

Password: •••••••••

Fig. 18. Login page



Current Date: 2022-12-29 16:35:56

76.54 Humidity (%)

27.59 Ambient Temperature (°C)

65 Light Intensity (Lux)

27.13 Soil Temperature (°C)

57.5 Soil Moisture (%)

Fig. 19. Main dashboard

Current Date: 2022-12-29 16:35:56

76.54 Humidity (%)

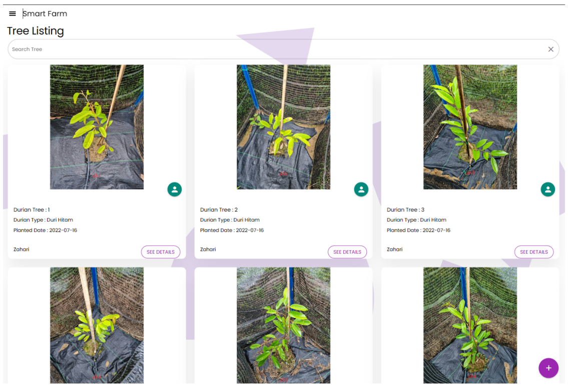
27.59 Ambient Temperature (°C)

65 Light Intensity (Lux)

27.13 Soil Temperature (°C)

57.5 Soil Moisture (%)

Fig. 20. Custom view of sensor data



Durian Tree : 1
Durian Type : Duri Hitam
Planted Date : 2022-07-16
Zahari

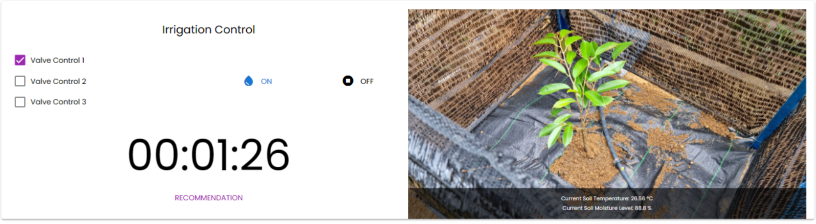
Durian Tree : 2
Durian Type : Duri Hitam
Planted Date : 2022-07-16
Zahari

Durian Tree : 3
Durian Type : Duri Hitam
Planted Date : 2022-07-16
Zahari

Fig. 21. Tree page

3.3 Irrigation System

The fuzzy irrigation system was implemented in the web system. The bottom section of the main dashboard contains the irrigation control for the farm. By default, the irrigation controller is in manual mode. The farmer manually selects the valve that they want to open and close. When the farmer clicks the on button, the control node will listen to the changes and open the chosen valve. While the valve was opening, the control node will also record the current soil moisture and soil temperature value. The data will be displayed in the picture in the web system. Once the water valve was stopped, the soil moisture and soil temperature value will be updated to reflect the newest condition of the soil. The irrigation control section also featured a stopwatch that record the time for the ongoing irrigation. Figure 22 shows the irrigation control section of the web system and the current soil moisture and temperature data.



00:01:26

Current Soil Temperature: 26.56 °C
Current Soil Moisture Level: 88.8 %

Fig. 22. Irrigation Control

The fuzzy irrigation system can be accessed at the recommendation button. The recommendation button is called the fuzzy logic API and passes the current sensor's data to the backend server. The backend server receives the current humidity, ambient temperature, light intensity, soil moisture, and soil temperature and inputs it to the fuzzy logic model to process it. The output of the fuzzy model is then passed back to the web system. The web system displays the result and changes the irrigation mode to automated mode. The irrigation will turn off automatically at the suggested time, which results in optimum irrigation time. Figure 23 shows the fuzzy output on the web system.

Suggestion

Irrigation Level : 100 %

Volume of Irrigation : 30 litre

Time of Irrigation : 1:0:00

00:00:00

Fig. 23. Fuzzy model output

3.4 System Testing

The system was deployed at the targeted farm from August 2022 to October 2022. One sensor node and three control nodes were installed at the farm. The sensor node record data from August 2022 to October 2022 without any down time. The data was recorded at the pace of every 10 minutes. The average of the recorded data was computed and displayed on the main dashboard. The average humidity around the farm was 82%, while the average ambient temperature was 29.85°C. The average soil temperature was 28.65°C, while the average soil moisture was 50%. The data shows that there was a relationship between the ambient temperature and the soil temperature as they had a similar reading. The average soil moisture throughout the month was lower as the average temperature was high and rain rarely happen; hence the soil moisture can't maintain its wetness throughout the day. Figure 24 and Figure 25 show the mean of the collected data.

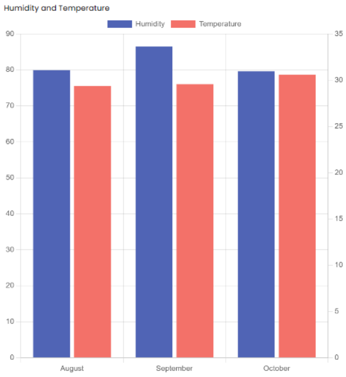


Fig. 24. Average humidity and ambient temperature data

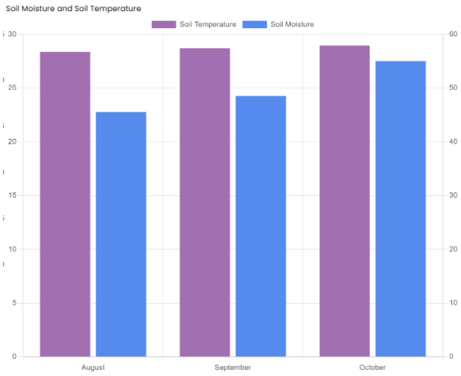


Fig. 25. Average soil temperature and soil moisture data

The farm site originally depends on manual irrigation, where farmers manually watered all the durian trees. The intelligent irrigation system replaces the traditional manual watering process, by allowing the farmer to remotely watered the durian tree with the exact volume of water that the tree needs. Compared to the traditional manual irrigation method, the fuzzy irrigation system shortens the time needed to complete the irrigation process. Data collection had been done throughout the 3-month trial period. The water volume consumption and the time taken for the irrigation was recorded and visualize in Figure 26 and Figure 27.

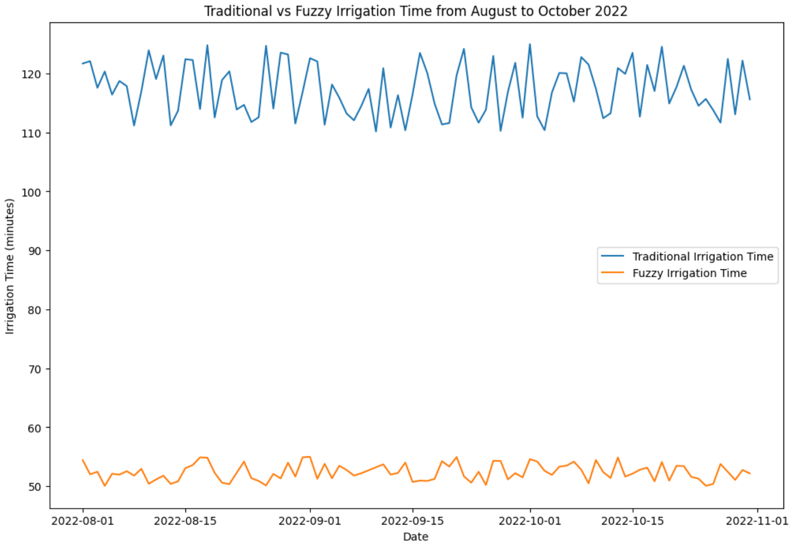


Fig. 26. Comparison between traditional and fuzzy irrigation time

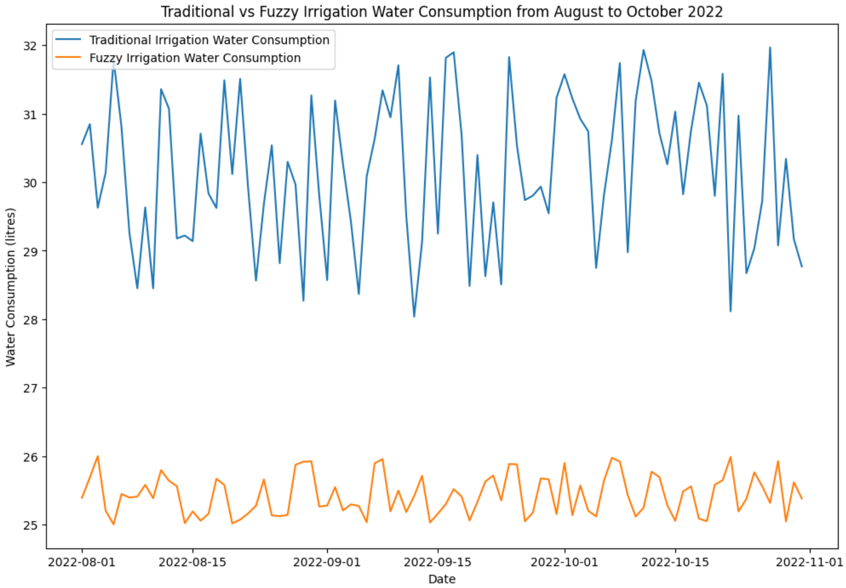


Fig. 27. Comparison between traditional and fuzzy water consumption

Based on the collected data, the average time needed for the farmer to finish irrigating all 65 trees took an average of two hours. The farmer reported that the average time to finish irrigation using fuzzy irrigation was 50 minutes. The volume of water that was used for irrigation was greatly reduced after the implementation of this system. Manual irrigation depends on the farmer's decision to turn off the water pipe, which caused the water volume used to become irregular. The fuzzy irrigation system stops the irrigation at a precise time thus the water used was more consistent. Based on the farmer from TW Megastar, a young durian tree needed 30-liter water to grow. As shown in Table 2, the fuzzy irrigation system was able to irrigate the durian tree with an average of 25 litres of water which didn’t overflow the durian tree. While the irrigation time was reduced significantly, the water volume only dropped by 25% because watering plants is not a direct function of time alone. The efficiency and precision in the fuzzy system is apparent in both reduced time and water volume, but the volume reduction is not as dramatic because there's an optimal amount of water that the trees need, and going below that would compromise the health of the trees.

Table 2
Comparison between traditional irrigation and fuzzy irrigation system

	Traditional Irrigation	Fuzzy irrigation
Time taken	2 hours	50 minutes
Water volume	Average of 35 litre	Average of 25 litre

The first three rows of durian tree that utilized the intelligent irrigation system shows a better growth rate when compared to the durian tree that used traditional irrigation. Figure 28 shows the durian tree that utilizes the intelligent irrigation system, while Figure 29 shows the durian tree that used the traditional irrigation method. Each tree was planted in the same month in February 2022. The durian tree that used the fuzzy irrigation system has a higher height and better growth rate.

Fig. 28. Durian tree that used intelligent irrigation system

Fig. 29. Durian tree that used traditional irrigation method

4. Conclusions

The system was successfully developed and deployed at the farm. Throughout the 3-month testing, the system had zero down time. This shows that the developed intelligent irrigation system was able to replace the traditional irrigation method. The manual labour activity during the irrigation process was also replaced by accessing the web system. Farmers could access the web system through their smart phones or computer and turn on the irrigation. This system is also able to provide an accurate estimation of water volume and time needed for irrigation. The testing shows that this system saves up to 60% of irrigation time and 25% of the water used. The water consumption for this system is more efficient as compared to the traditional irrigation method. The fuzzy logic model was deployed on a cloud server, where it served as a backend API. This reduces the needs of setting up a computing unit at in the farm area which reduces the operation cost for the farm.

4.1 Future Works

Although the system has been successfully implemented at the farm, future enhancements could include refining the fuzzy logic model by incorporating the evaporation and transpiration rate of water for more accurate water needs assessment. A significant advancement would be the integration of drones equipped with advanced sensors. These drones can capture high-resolution images, providing real-time data on land use, soil content, and vegetation health, including the Normalized Difference Vegetation Index (NDVI). This information can be integrated into the fuzzy logic model to further refine irrigation precision. Additionally, the introduction of a scheduler control mode would allow farmers to plan their irrigation up to 3 days in advance. Utilizing predictive models based on historical sensor data can also enhance the data used in the fuzzy logic model.

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