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Smart fertigation system with mobile application and fuzzy logic optimization

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Abstract

Precision farming plays a pivotal role in addressing the dual challenge of increasing crop productivity and reducing the environmental impact of agriculture. This arises from the critical need to elevate crop productivity to meet the increasing global demand for food, while actively confronting the economic and environmental consequences linked to suboptimal conventional farming practices. Conventional agriculture consistently grapples with inefficiencies in resource management, marked by the impractical and excessive utilization of fertilizers and water. This not only results in mounting production costs, but also gives rise to substantial threats to the environment, encompassing soil degradation, water pollution, and the loss of biodiversity. Thus, this study introduces a smart fertigation system, incorporating internet of things (IoT) technology and fuzzy logic optimization, specifically designed for large-scale bird's eye chili production. The innovative system integrates IoT technology with fuzzy logic to fine-tune fertilization and irrigation processes. Notably, a fuzzy inference system, implemented using MATLAB and Arduino UNO, dynamically optimizes nutrient delivery according to the growth stage of the chili plants. This sophisticated approach ensures that fertilization is precisely tailored to the specific needs of the crops at each developmental phase. Additionally, the development of the C-farm mobile application empowers farmers with remote monitoring capabilities, enabling them to oversee and manage the system from anywhere. This mobile application provides real-time insights into the smart fertigation system , granting farmers unprecedented control over their agricultural operations. Our findings also highlight the efficacy of fuzzy logic in enhancing the precision of automated fertigation systems. By dynamically adjusting nutrient delivery in response to the nuanced growth stages of chili plants, our system demonstrates its adaptability and responsiveness, resulting in optimized resource utilization and improved crop outcomes. This innovative integration of technology not only holds promise for large-scale crop production but also addresses the pressing issues of water and fertilizer waste in contemporary agriculture. Moving towards a more sustainable and efficient agricultural paradigm, the smart fertigation system, featuring fuzzy logic optimization and remote monitoring capabilities, stands as a beacon of progress in the quest for precision farming.

Keywords

Smart fertigation, Precision agriculture, Fuzzy logic, Arduino UNO, Bird's eye chili.

1.Introduction

In Malaysia, the agricultural sector plays a vital role as it provides food, which is the most fundamental human necessity. Fertigation is a crucial technique used to improve crop yields by combining fertilization with an irrigation system. It is more efficient than traditional fertilization, reduces soil erosion and water consumption, and regulates the release of fertilizer.

With the projected rise in food demand estimated to reach 59 to 98 percent by 2050 [1] farmers will need to enhance crop production either by adding more agricultural areas or improving productivity on current lands. However, traditional agricultural methods are insufficient for producing substantial amounts of crops and require a significant amount of human labor, time, and money.

Recent decades have seen significant technological advancements in agriculture, making it more industrialized and technology driven. The internet of things (IoT) and mobile applications [2–4] are now

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being used in fertigation systems to reduce labor costs and time. These advancements aim to improve agricultural production in both quality and quantity, including the production of bird's eye chilies, which is a popular spice in traditional Southeast Asian cuisine, particularly in Malaysia, Indonesia, and Thailand [5–8]. However, despite the presence of commercial bird's eye chili growers in Malaysia, the country still imports a significant amount from other countries due to limited local production. Addressing the challenge of achieving mass production of bird's eye chilies within a technological and industrial framework requires a nuanced approach. The fusion of IoT technology, mobile applications, and advanced agricultural practices, as proposed in this study, presents a potential solution to this predicament. By harnessing the power of technology-driven precision farming, the system aims to create an environment where bird's eye chili plants can flourish on a substantial scale, contributing to the reduction of import dependency and bolstering local production capabilities.

A smart fertigation system was proposed in this paper with mobile application and fuzzy logic optimization designed to address the challenges faced by farmers in traditional agricultural practices. The use of fuzzy logic artificial intelligence (AI) in such a system allows for accurate determination of water and fertilizer distribution rate based on data collected from the embedded sensors. To ensure efficient water and fertilizer usage, a mobile application has been developed to display data from the sensors and monitor water and fertilizer usage. By using this system, farmers can save time and reduce labor costs, while also increasing productivity and efficiency. Thus, the main objective of this study is to design an IoT-based automation fertigation system, develop a mobile application that can be used to monitor the system, and implement fuzzy logic in decision-making processes to increase the accuracy on volume of water and fertilizer that the plant needs based on the plant growth phase (root, leafy & fruit phase). The scope of this study primarily focuses on the production of the bird’s eye chili plant for large-scale agricultural businesses.

The contribution of this study lies in its holistic approach to optimize crop production through the integration of IoT technology and fuzzy logic optimization. By addressing key challenges in agriculture, such as resource wastage and environmental impact, the study offers a potential solution that aligns with sustainable and efficient farming practices.

The structure of this paper is organized as follows: Section 2 provides an in-depth review of the relevant literature, contextualizing the study within the existing body of knowledge. Section 3 offers a detailed presentation of the proposed methodology and system design. The results and analyses emanating from the study are presented in Section 4. Section 5 synthesizes the findings and provides a discussion. The final section, Section 6, concludes the study, summarizing the key takeaways and offering insights into potential future research directions.

2.Literature review

This study is of four significant substantial for their distinct purposes. It starts with the development of an IoT-based automation fertigation system, mainly to optimize the delivery of water, and nutrients to the plants besides others. The second component involves the incorporation of AI, enhancing the system's decision-making capabilities. The third component centers on the practical application of the system, where users can interact with and monitor the automation process. And lastly, the bird's eye chili plants care, that focuses on ensuring their growth throughout the process.

2.1IoT-based automation fertigation system

The integration of IoT technology into fertigation systems holds great potential for revolutionizing farm management and decision-making, thereby assisting farmers in optimizing crop production and resource utilization [9]. However, it's important to acknowledge the limitations surrounding the adoption of IoT technology, as not all farmers have the same access to advanced technology due to various reasons such as affordability, connectivity, and technical skills. This limitation may delay the widespread adoption of such systems, and it's important to consider the digital divide and accessibility issues.

In many existing fertigation systems, a common approach involves the utilization of at least two sensors as input parameters. For example, a study by Ahmed et al. [10] incorporated soil moisture and pH sensors as input parameters in their automated fertigation system. While this approach is effective for many crops, it may not be universally applicable, as different crops have varying requirements and environmental conditions. The system's reliance on preset values for pH and electrical conductivity (EC) adjustments may not account for all potential variations in soil types and crop species, presenting a limitation.

Another intelligent fertigation system developed by Ruan et al. [11] relied on pH and EC sensors. However, a limitation here is that these sensors may need to be maintained and calibrated regularly. This regular maintenance and calibration can be a burden for farmers, especially for those with limited technical expertise. Furthermore, these sensors may not address the full spectrum of nutrient requirements for various crops, leaving room for refinement.

On the other hand, Joseph et al. [12] picked a streamlined approach. It is done by employing a single soil moisture sensor in their automation fertigation system to detect soil moisture content. This approach may simplify user interaction. Unfortunately, it can also limit the system's adaptability. It depends on user input for fertilizer-related decisions, which may not align with the goal of reducing human intervention. Moreover, the success of such a system depends on the accuracy of the soil moisture sensor, and any calibration issues can lead to imprecise decisions, presenting a limitation.

Meanwhile, [13] proposed a solar fertigation system that uses solar power as its energy source. The system aims to determine the optimal water and nutrient requirements of plants based on agronomic models and sensor data. The system then calibrates the fertilizers' levels to be used during irrigation and fertigation, as well as the timing of irrigation scheduling. However, the proposed system may not be practical. This is due to the complex data, thus it needs for irrigation and fertigation processes. The decision-making process relies on intelligent analysis of various factors such as soil sensors, weather conditions, crop type, and IoT analysis. Moreover, the system also collects data on the temperature and humidity of both the soil and atmosphere, therefore, increasing the complexity of the data.

Long range wide area network (LoRaWAN) based internet of thing s (IoT) system for precision irrigation in plasticulture fresh-market tomato. Sensors are utilized for real-time data monitoring and automating irrigation systems [14]. This is mainly to save water in crop production and can be used as a precision management tool for fresh-market tomato production. However, this system focuses only on fresh-market tomato production and may not be generalizable for other crops or production systems. Meanwhile, [15] proposed smart IoT system for chili production using long range (LoRa) technology. The system uses IoT devices such as sensors, pumps, and valves to monitor and automate the operations of growing chili. The system can be used for real-time data collection, monitoring, and analysis of various parameters such as soil moisture, temperature, and humidity. This is believed to assist farmers in optimizing their production processes, reduce costs, and increase yields. However, it is worth to note the economic feasibility and technical limitations of these systems before implementing them on a large scale farming system.

Aside from that, IoT-based solutions can increase agricultural yields and automate a variety of farming chores by using smart devices and digital technology [16], using sensors, communication technology, Arduino devices, and other devices to gather data in real-time and regulate variables such as temperature, humidity, light, and soil moisture. They work well for accurate irrigation and for automating tasks like harvesting, pest control, fertilisation, and caring for livestock. Consequently, it benefits farmers by reducing expenses while simultaneously increasing yields. Before implementing these systems broadly, it's crucial to consider their costs and technical difficulties, as the research to date does not provide this information, and further research is required to ensure that they are useful and feasible for farmers.

In [17], the system uses IoT devices like sensors and Wi-Fi modules to watch over soil moisture in fertigation systems, allowing real-time data analysis. This helps farmers improve their fertigation methods, cut costs, and increase crop yields. Research papers explain how IoT technology can revolutionize farming by remotely managing soil moisture levels in fertigation. They suggest that IoT-based systems can transform food production and resource management in agriculture. However, this system does not consider the real-time monitoring that can assist farmers [17]. However, the monitoring is restricted to the Blynk application, which lacks extensive customization. Blynk provides a set of predefined widgets, but the limited customization options can pose challenges when trying to design highly specialized or unique IoT interfaces.

To summarize, the integration of IoT technology into fertigation systems is recognized for its potential to revolutionize farm management, optimize crop production, and enhance resource utilization.

However, the adoption of IoT faces challenges, including accessibility issues due to factors such as affordability, connectivity, and technical skills, which may hinder widespread implementation. Existing fertigation systems often rely on multiple sensors, each with its limitations, ranging from applicability across different crops to the need for regular maintenance and calibration. Streamlining approaches, such as utilizing a single soil moisture sensor, may simplify user interaction but could limit system adaptability and depend on user input for fertilizer decisions. Innovative proposals, like the solar fertigation system, present challenges due to the complexity of data requirements for irrigation processes. Specific IoT systems targeting fresh-market tomato or chili production show promise but underscore the importance of considering economic feasibility and technical limitations before large-scale implementation. Overall, while IoT-based solutions hold potential to enhance agriculture by automating tasks and remotely managing soil moisture, careful consideration of costs, technical challenges, and customization options is crucial for ensuring practicality and feasibility for farmers.

2.2Implementation of AI into automation fertigation system

In the realm of smart farming, numerous studies have explored a diverse range of applications for AI and machine learning (ML). These investigations span from precision agriculture and crop monitoring to automated livestock management and predictive analytics for disease detection.

In [13], it emphasizes the pivotal role of ML algorithms in tasks such as crop selection and management. These algorithms leverage data on soil quality, compatibility classification, and other factors, enabling informed decisions about crop choices.

In a related review, [14] examines the automation and digitization of agriculture and underscores the benefits of employing technology for sustainable crop production. The references suggest that AI and IoT-based systems have the potential to optimize water and nutrient management, reduce labor costs, and enhance crop production.

Moreover, [18] proposed an automated irrigation and fertilization system that utilizes fuzzy logic to control sensors. Their system incorporates two input membership functions for soil moisture and pH value and three output membership functions for water flow, acid solution, and alkali solution. This shows how versatile is the smart technologies in agriculture, significantly increasing crop yields.

Similarly, [19] applied fuzzy logic in their fertigation system. By doing so, the intelligent irrigation decisions are made based on data from soil moisture, temperature, and humidity sensors. This approach has been proven to enhance irrigation. Furthermore, [20] integrated both ML and deep learning in their fertigation system. The accuracy of different ML algorithms are compared, such as naive bayes, logistic regression, support vector machine, decision tree classifier, bagging classifier, random forest classifier, adaboost classifier, gradient boosting classifier, xgboost classifier, and k-nearest neighbor. From this study, it can be concluded that efficiency can be increased and the process is simplified when ML are used in agricultural application. In conclusion, the implementation of AI in fertigation systems can greatly benefit agriculture, leading to more efficient and cost-effective crop production. The choice of algorithm depends on the specific requirements of the system, and it is essential to compare and evaluate the different approaches before implementing them.

Proposed an automated irrigation and fertilization system that uses fuzzy logic to control sensors [18]. Their system has two input membership functions for soil moisture and pH value and three output membership functions for water flow, acid solution, and alkali solution. With the help of smart technologies, agriculture is now capable of producing significantly more crops than before. Similarly, used fuzzy logic in their fertigation system to make intelligent irrigation decisions based on data from soil moisture, temperature, and humidity sensors. The fuzzy logic-based fertigation method increased irrigation application efficiency by 50 percent and produced a larger growth gradient and chili production compared to traditional methods. It propose an automated system that uses an artificial neural network (ANN) algorithm for intelligent decision-making. ANN is a popular algorithm for forecasting and making predictions based on parallel reasoning, which simulates the human brain's functioning.

Furthermore, [20] integrated both ML and deep learning in their fertigation system. They compared the accuracy of different ML algorithms, such as naive bayes, logistic regression, support vector machine, decision tree classifier, bagging classifier, random forest classifier, AdaBoost classifier, gradient boosting vlassifier, XGBoost classifier, and K-nearest neighbor. Their study concluded that using ML in agricultural applications can significantly increase efficiency and simplify the process. In conclusion, the implementation of AI in fertigation systems can greatly benefit agriculture, leading to more efficient and cost-effective crop production. The choice of algorithm depends on the specific requirements of the system, and it is essential to compare and evaluate the different approaches before implementing them.

In the realm of smart farming, diverse studies explore the applications of AI and ML. These investigations range from crop management to disease detection, highlighting the pivotal role of ML algorithms in informed decision-making, as seen in [13]. Additionally, [14] emphasizes the benefits of employing AI and IoT-based systems for optimizing water and nutrient management. Noteworthy contributions from [19, 20] showcase the versatility of smart technologies, utilizing fuzzy logic and integrating ML and deep learning to significantly enhance irrigation decisions and increase overall crop production efficiency. The proposed automated system in [18] further exemplifies the potential of fuzzy logic and artificial neural networks (ANN) for intelligent decision-making, underscoring the transformative impact of these technologies on agriculture. Overall, the implementation of AI and ML in fertigation systems holds significant promise for advancing efficiency and cost-effective crop production, contingent on careful consideration of specific system requirements and algorithm choices.

2.3Application usage in automation fertigation system

The study conducted by [12] can be conveniently monitored via a mobile application. They use Blynk mobile application as the user interface. Blynk is an Arduino-controlling mobile application that runs on the internet. By using the Blynk application, they can input nitrogen, phosphorus and potassium (NPK) requirements, fertilizer concentrations, soil moisture content status, start or stop commands, and irrigation mode. Also, they can use the application to monitor the plant's condition without having to physically visit the farm. But their application is not good enough since they still need to control the usage of the fertilizers in the application manually and it does not meet the purpose of reducing human labour.

Like [12, 18, 21, 22] also used mobile applications to monitor their proposed system. The data is stored by the system and display on the farmers' device using mobile application. In our opinion, to consistently supply plants with enough nutrients and moisture, proper monitoring and control of irrigation and fertilization systems are essential.

Nevertheless, the automated fertigation system proposed by [9] is using the web as the user interface. Farmers can utilize the web as an interface to interact with the system. The farmers can access the web using mobile devices such as phones and tablets to monitor the system, change the fertigation routine, and set the combination formula of EC. However, mobile applications are the preferred choice for farmers to access and monitor their fertigation systems while working in the field. They are user-friendly, intuitive and provide convenience on site. If the farmers wanted to make some adjustments to their systems, they can just easily do it through mobile apps. They can also stay connected to receive real-time alerts and notifications as they go around their farms.

On the other hand, [23] simplifies communication by incorporating Telegram bot applications for automated mobile messaging. Additionally, web-based applications are hosted in the cloud, enhancing accessibility. Nevertheless, it's crucial to acknowledge a limitation in this context—the absence of a dedicated mobile interface for real-time access to the fertigation system in the dynamic farming environment.

In contrast, [9] utilizes the web as its user interface for the automated fertigation system. By using mobile devices such as phones and tablets, farmers are able to interact with the system through web access. This allows them to monitor the system, adjust the fertigation routine, and customize the EC combination formula. However, it's noteworthy that mobile applications remain the preferred choice for farmers working in the field. Mobile apps offer user-friendliness, intuitive operation, and on-site convenience. They enable farmers to make necessary adjustments to their systems effortlessly while staying connected to receive real-time alerts and notifications as they navigate their farms. This level of mobility and real-time monitoring aligns well with the dynamic nature of farming, where quick responses to changing conditions are essential.

In short, the examination of how farmers interact with automated fertigation systems highlights two primary methods: through mobile applications and web interfaces. In the case of the blynk mobile application used in one study, it provides convenient monitoring capabilities, allowing users to input crucial parameters. However, a notable drawback emerges as manual control of fertilizer usage is still required. Similarly, other studies favor mobile applications, emphasizing the importance of vigilant monitoring for maintaining consistent nutrient supply. In contrast, another study opts for a web-based interface, recognizing its accessibility advantages while acknowledging the prevailing preference among farmers for mobile applications due to their on-site convenience and real-time monitoring. Introducing a Telegram bot application simplifies communication in a different study but introduces a limitation by lacking a dedicated mobile interface for immediate access. This analysis underscores the practical considerations in choosing user interfaces, emphasizing the need for seamless automation and on-site convenience in dynamic farming environments. It also suggests avenues for future research to enhance user experiences and simplify smart farming technologies for farmers.

2.4Bird Eye's chili plant care

The bird's eye chili is scientifically known as Capsicum frutescens [24]. Caring and measuring chili plant in terms of research can be seen in [25]. It proposed a more efficient way to measure the height and width of these plants in the field, which is traditionally done manually. This innovative approach uses special devices like sensors, relays, and Wi-Fi to take the measurements automatically. It also allows for the real-time collection and analysis of soil moisture data. The research papers discuss the development and application of systems that utilize image processing to monitor plant growth in the field from a distance. This technology is seen as promising for farmers, but it's important to note that the study's scale was relatively small, and it's suitability for large-scale agriculture may require further exploration.

To care for chili plants, it does not only involve fertilization; proper watering is also an important factor to be taken care of. Often, watering can be irregular, and caregivers may overlook factors like temperature and soil moisture [26]. In addition, due to other commitments, caregivers may find it hard and challenging to maintain a consistent watering schedule, thus, potentially leading to suboptimal chili plant growth or even causes death. To solve this, ideal watering times are utilized using Arduino and other various sensors. From this research, data are collected from sensors, including soil moisture, air humidity, temperature, and ultrasonic sensors. Then, the data is transmitted to a website for user access. Sensors are devices that detect changes in physical conditions like pressure, light, temperature, and more.

They are small but productive chili plants [27]. Bird's eye chili is a popular spice all around the world and believed to be originated in Asia. They are frequently used in cooking and salads throughout India and Asia, particularly. The bird's eye chili is a tiny plant with small fruits. The pods are approximately 5cm long and 1cm in diameter. According to [27] during the germ phase, seed germination might be harmed by pre-fertilized growth substrate. For the initial days after germination, the chili seed has adequate compounds. We start to fertilize the plants after they have developed more leaves. The seedling dosage must be kept as low as possible. High nutrient salt concentrations are vulnerable to young plants.

During the first four months of growth, we must use a fertilizer with a higher nitrogen (N) concentration [27]. The nitrogen content can be shown by the NPK value. When the NPK value is 3-1-4, it indicates that the fertilizer contains 3% nitrogen, 1% phosphorus, and 4% potassium. Nitrogen is necessary for plant growth. Root growth is aided by phosphorus, while flowering and fruit creation are aided by potassium. It is essential to keep the soil damp. Dry soil and the usage of liquid fertilizer may cause damage to the roots.

The aim for this study is to measure soil moisture, air humidity, and temperature to determine the best times to water chili plants using these sensors, as it eases the farmers' work to monitor and care for them. Through Blackbox testing, the system's effectiveness is confirmed, showing that it meets expectations and functions well. Despite that, it's important to note that this study is done in a controlled environment and may not fit for large-scale plant production.

To summarize, bird eye's chili plant care delves into the cultivation practices of capsicum frutescens, a globally popular spice native to Asia. Most of the studies provides practical insights, highlighting the importance of nitrogen-focused fertilization and specific NPK values during the initial growth phase. Beyond fertilization, the literature addresses challenges in watering practices, emphasizing the need for consistency and the potential consequences of irregular watering. The integration of advanced technologies, such as sensors and Wi-Fi, for automated measurement and real-time data collection in chili plant care is explored. While recognizing the effectiveness of these technologies through testing, the literature acknowledges the need for further research, especially in scaling up image processing systems for plant growth monitoring and assessing the adaptability of Arduino-based watering systems in diverse environments. The study's implications include practical recommendations for farmers and stress the continual importance of innovation in smart agricultural practices.

3.Methods

The smart fertigation system with mobile application and fuzzy logic optimization was developed using an agile model [4, 27, 28] that makes iterative development, fast feedback, and adjusting at every level of the product cycle their priority. The development cycle consists of three iterations. Each iteration focuses on a specific aspect of the product. During the first iteration, the hardware development of the IoT-based fertigation system was the primary focus. The second iteration was dedicated to the development of the C-Farm mobile application, which was created using Flutter [29–31]. The third iteration involved the implementation of fuzzy logic into the system. Each iteration consisted of six phases, and *Figure 1* provides an overview of the mobile application development process for an automated fertigation system using fuzzy logic [32]. However, for the purpose of this study, we will primarily focus on the fuzzy logic aspect of the development since it is the main idea behind the development of this product. *Figure 2* shows an architectural overview of the proposed mobile application automated fertigation system employing fuzzy logic as a decision-making engine. It consists of five elements which include the hardware setup of the fertigation system, Arduino for data collection, fuzzy logic algorithm for data processing and decision making, cloud firestore database, and C-farm application.

Figure 1 Development of the fuzzy logic based automation

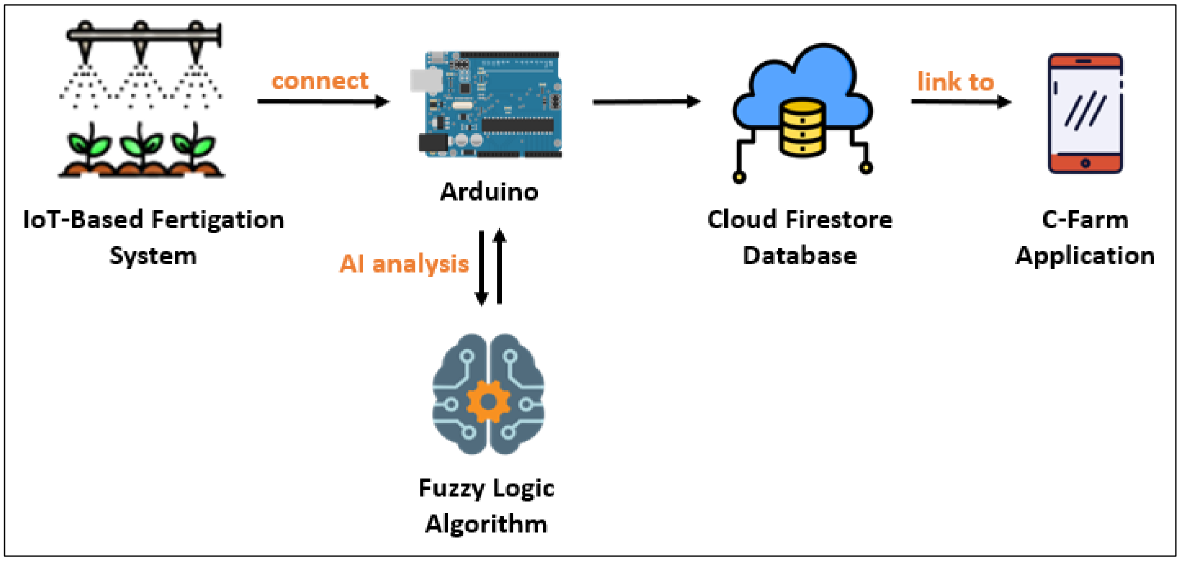


Figure 2 Fuzzy logic based automation Fertigation system with mobile application

Sensors has been used to read data twice a day at predetermined times: 8:00 AM and 5:00 PM. The collected data will be processed by fuzzy logic algorithm to produce outputs for irrigation and fertilization purposes. The system will then carry out three distinct procedures simultaneously. The initial step involves checking the state of irrigation; followed by the watering status for the plant, when needed, the water pump is activated by the system for a predetermined duration determined by fuzzy logic output. The next step involves the fertilization status; depending on the plant's growth phase and nutrient requirements, the nitrogen (N), phosphorous (P), and potassium (K) pump will be turned on for a duration determined by the output of the fuzzy logic. and lastly, if the plant does not require irrigation or fertilization, the system continues collecting data from the sensors as usual. The data collected by the system will be stored in the cloud firestore, and this data will be used in the third procedure to display information in the C-farm mobile application. The complete flow of the system can be seen in *Figure 3*.

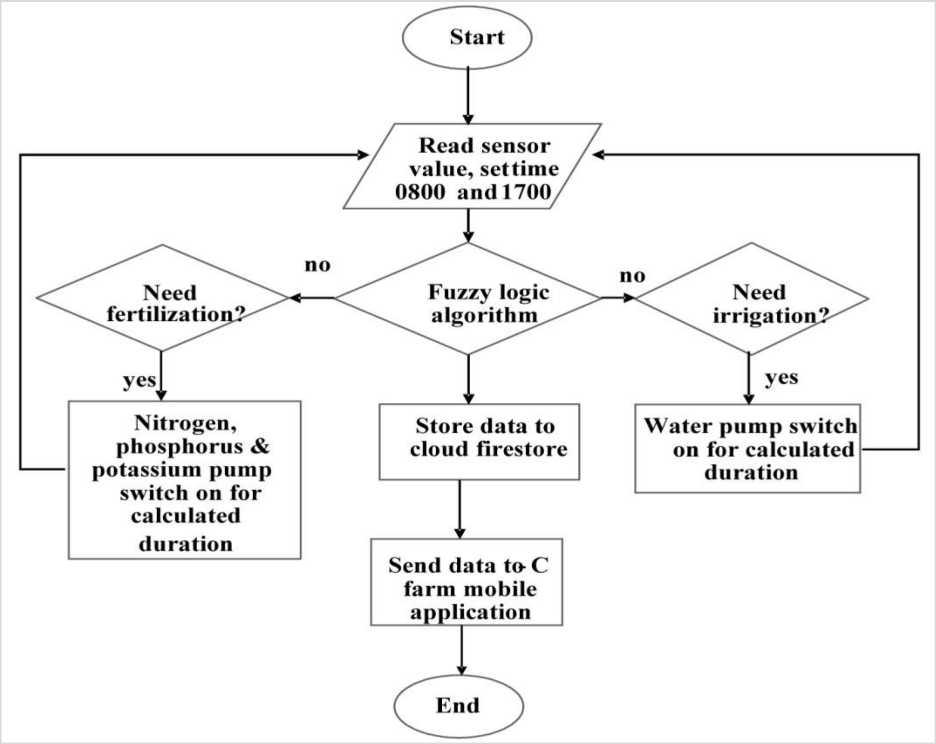


Figure 3 Flowchart for the proposed automated Fertigation system

3.1Hardware and software overview

A well design of the hardware setup ensures the reliability of the system and choosing suitable hardware and software is essential to build a good and successful system. *Table 1* enumerates the hardware and software components employed in the development of the Smart fertigation system with mobile application and fuzzy logic optimization.

Table 1 Hardware and software

Hardware	Software
Arduino UNO	Arduino IDE
NodeMCU	Fritzing
Breadboard	MATLAB
Jumper Wire	Google Firebase
Micro Submersible Water Pump	Visual Studio Code
Water Pipe	NA
9V Battery	NA
9V Battery Clip	NA
8-Ways Relay Module	NA
MAX485 TTL to RS485 Module	NA
Soil Moisture Sensor	NA
DHT22 Sensor	NA
NPK Sensor	NA

3.2Fuzzy irrigation system

The foundation of our automated fertigation system relies on fuzzy set theory. Fuzzy inference system is a process of mapping from a given input to an output, using the theory of fuzzy sets. This system used Mamdani method [33, 34] for the fuzzy inference system. *Figure 4* shows the mapping of fuzzy inputs to the respective fuzzy set theory prior producing fuzzy output for the irrigation system.

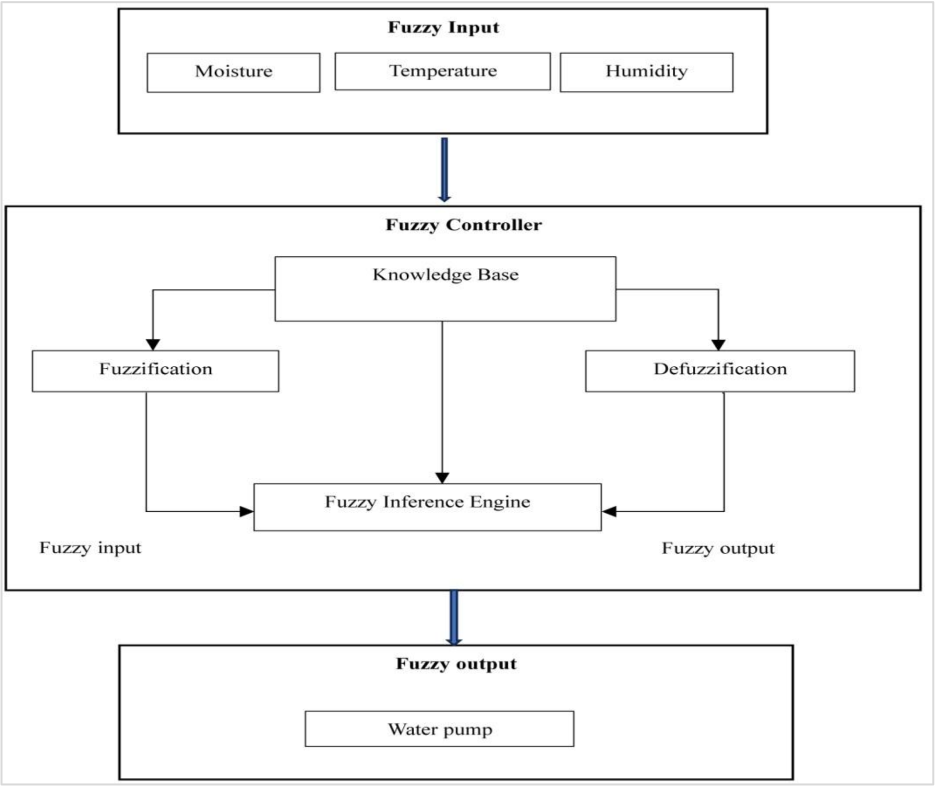


Figure 4 Fuzzy irrigation system

3.3Crisp input and fuzzification

The system, which comes with a Mobile Application, takes in three inputs: soil moisture, temperature, and humidity. To define these inputs, the system uses three linguistic regions: 'DRY', 'MEDIUM', and 'WET' for soil moisture, 'LOW', 'MEDIUM', and 'HIGH' for humidity, and 'COLD', 'WARM', and 'HOT' for temperature [18, 21, 35]. The membership functions for the soil moisture, humidity, and temperature sensors were generated using MATLAB [36–38] and are illustrated in *Figure 5*, *6*, and *7* respectively. Meanwhile, *Table 2* provides a summary of the input variable for the sensors using the Mamdani method.

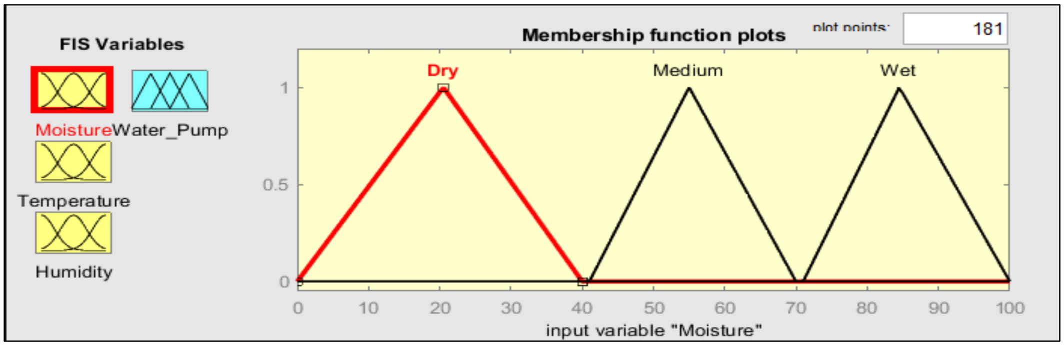

plot points: 181

Figure 5 Membership function for soil moisture sensor

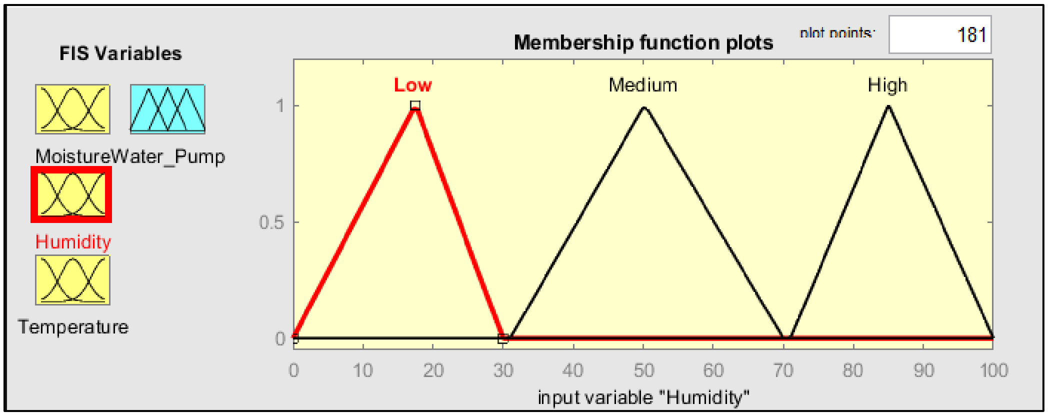


Figure 6 Membership function for humidity sensor

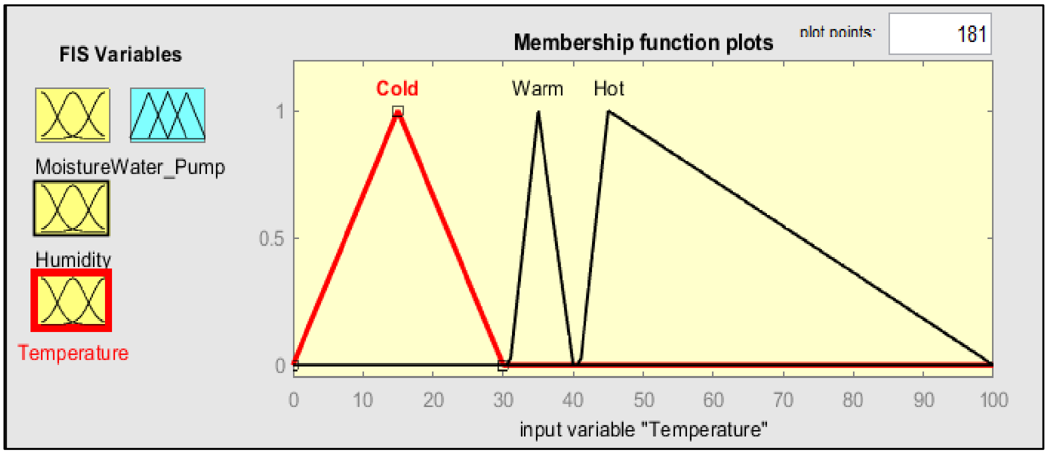


Figure 7 Membership function for temperature sensor

Table 2 Output description of each pump

Sensor	Name of MF	MF Type	Range	Parameters
Soil Moisture	Dry	Triangular	(0, 100)	(0, 20.5, 40)
	Medium	Triangular	(0, 100)	(41, 55, 70)
	Wet	Triangular	(0, 100)	(71, 84.5, 100)
Humidity	Low	Triangular	(0, 100)	(0, 17.5, 30)
	Medium	Triangular	(0, 100)	(31, 50.2, 70)
	High	Triangular	(0, 100)	(71, 85, 100)
Temperature	Cold	Triangular	(0, 100)	(0, 15, 30)
	Warm	Triangular	(0, 100)	(31, 35, 40)
	Hot	Triangular	(0, 100)	(41, 45, 100)

3.4Knowledge based rule

In order to support approximative reasoning, knowledge base systems use fuzzy knowledge bases that rely on fuzzy set theory to represent facts, rules, and linguistic variables. In this system, each of the three input variables - soil moisture, temperature, and humidity - has three linguistic variables. This means that there are 27 rules for the input parameters, which can be seen in *Figure 8.*

3.5Defuzzification and crisp output

When a crisp input is fuzzified to create a fuzzy value, this process is called defuzzification. The fuzzy output as the result of fuzzy inference engine is converted into a crisp value that can be forwarded to the controller. The resulting fuzzy results cannot be applied to any application where decisions must only be based on crisp values and the controller only comprehends crisp output. As a result, the fuzzy output needs to be changed into a crisp value. *Figure 9* shows the membership function for water pump rate from MATLAB. The output for this membership function is in unit second. Using Mamdani, method, *Table 3* exhibits the state of output variable for water pump. The water pump rate is measured in unit second.

1. If (Moisture is Dry) and (Humidity is Low) and (Temperature is Cold) then (Water_Pump is Medium) (1)
2. If (Moisture is Dry) and (Humidity is Low) and (Temperature is Warm) then (Water_Pump is Medium) (1)
3. If (Moisture is Dry) and (Humidity is Low) and (Temperature is Hot) then (Water_Pump is Medium) (1)
4. If (Moisture is Dry) and (Humidity is Medium) and (Temperature is Cold) then (Water_Pump is Medium) (1)
5. If (Moisture is Dry) and (Humidity is Medium) and (Temperature is Warm) then (Water_Pump is Medium) (1)
6. If (Moisture is Dry) and (Humidity is Medium) and (Temperature is Hot) then (Water_Pump is Medium) (1)
7. If (Moisture is Dry) and (Humidity is High) and (Temperature is Cold) then (Water_Pump is Medium) (1)
8. If (Moisture is Dry) and (Humidity is High) and (Temperature is Warm) then (Water_Pump is Medium) (1)
9. If (Moisture is Dry) and (Humidity is High) and (Temperature is Hot) then (Water_Pump is Medium) (1)
10. If (Moisture is Medium) and (Humidity is Low) and (Temperature is Cold) then (Water_Pump is Short) (1)
11. If (Moisture is Medium) and (Humidity is Low) and (Temperature is Warm) then (Water_Pump is Short) (1)
12. If (Moisture is Medium) and (Humidity is Low) and (Temperature is Hot) then (Water_Pump is Short) (1)
13. If (Moisture is Medium) and (Humidity is Medium) and (Temperature is Cold) then (Water_Pump is Short) (1)
14. If (Moisture is Medium) and (Humidity is Medium) and (Temperature is Warm) then (Water_Pump is Short) (1)
15. If (Moisture is Medium) and (Humidity is Medium) and (Temperature is Hot) then (Water_Pump is Short) (1)
16. If (Moisture is Medium) and (Humidity is High) and (Temperature is Cold) then (Water_Pump is Short) (1)
17. If (Moisture is Medium) and (Humidity is High) and (Temperature is Warm) then (Water_Pump is Short) (1)
18. If (Moisture is Medium) and (Humidity is High) and (Temperature is Hot) then (Water_Pump is Short) (1)
19. If (Moisture is Wet) and (Humidity is Low) and (Temperature is Cold) then (Water_Pump is Short) (1)
20. If (Moisture is Wet) and (Humidity is Low) and (Temperature is Warm) then (Water_Pump is Short) (1)
21. If (Moisture is Wet) and (Humidity is Low) and (Temperature is Hot) then (Water_Pump is Short) (1)
22. If (Moisture is Wet) and (Humidity is Medium) and (Temperature is Cold) then (Water_Pump is Short) (1)
23. If (Moisture is Wet) and (Humidity is Medium) and (Temperature is Warm) then (Water_Pump is Short) (1)
24. If (Moisture is Wet) and (Humidity is Medium) and (Temperature is Hot) then (Water_Pump is Short) (1)
25. If (Moisture is Wet) and (Humidity is High) and (Temperature is Cold) then (Water_Pump is Short) (1)
26. If (Moisture is Wet) and (Humidity is High) and (Temperature is Warm) then (Water_Pump is Short) (1)
27. If (Moisture is Wet) and (Humidity is High) and (Temperature is Hot) then (Water_Pump is Short) (1)

Figure 8 Irrigation IF-THEN rules

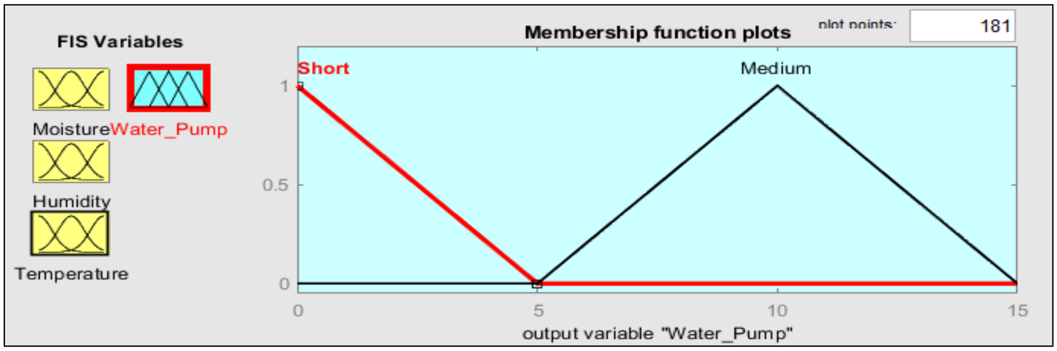


Figure 9 Membership function for water pump rate

Table 3 Description of water pump

Sensor	Name of MF	MF Type	Range	Parameters
Water Pump	Short	Triangular	(0, 15)	(-5, 0, 5)
	Medium	Triangular	(0, 15)	(5, 10, 15)

3.6Fuzzy fertilization system

Figure 10 shows how the fuzzy inputs are mapped to fuzzy output via the use of fuzzy set theory for the fertilization system. Depending on the stage of plants' growth, the fuzzy logic for fertilization is different. This is due to the different NPK fertilizer ratios during each stage.

3.7Crisp input and fuzzification

The system receives nitrogen, phosphorus, and potassium as three crisp inputs. This system defines all the input variables according to three linguistic regions: "LOW", "MEDIUM", and "HIGH". The parameter values in the input description below vary according to the stage of plant growth. This resulted from the various NPK fertilizer ratios used at each phase.

3.8Root phase

The root growth is aided by phosphorus (P). Thus, the NPK fertilizer ratios for the root phase are 1-2-1. The membership function of the nitrogen, phosphorous, and potassium sensor for the root phase is displayed in *Figure 11*, *12* and *13* respectively. Based on Mamdani method, *Table 4* exhibits the state of the input variable of phosphorous sensor.

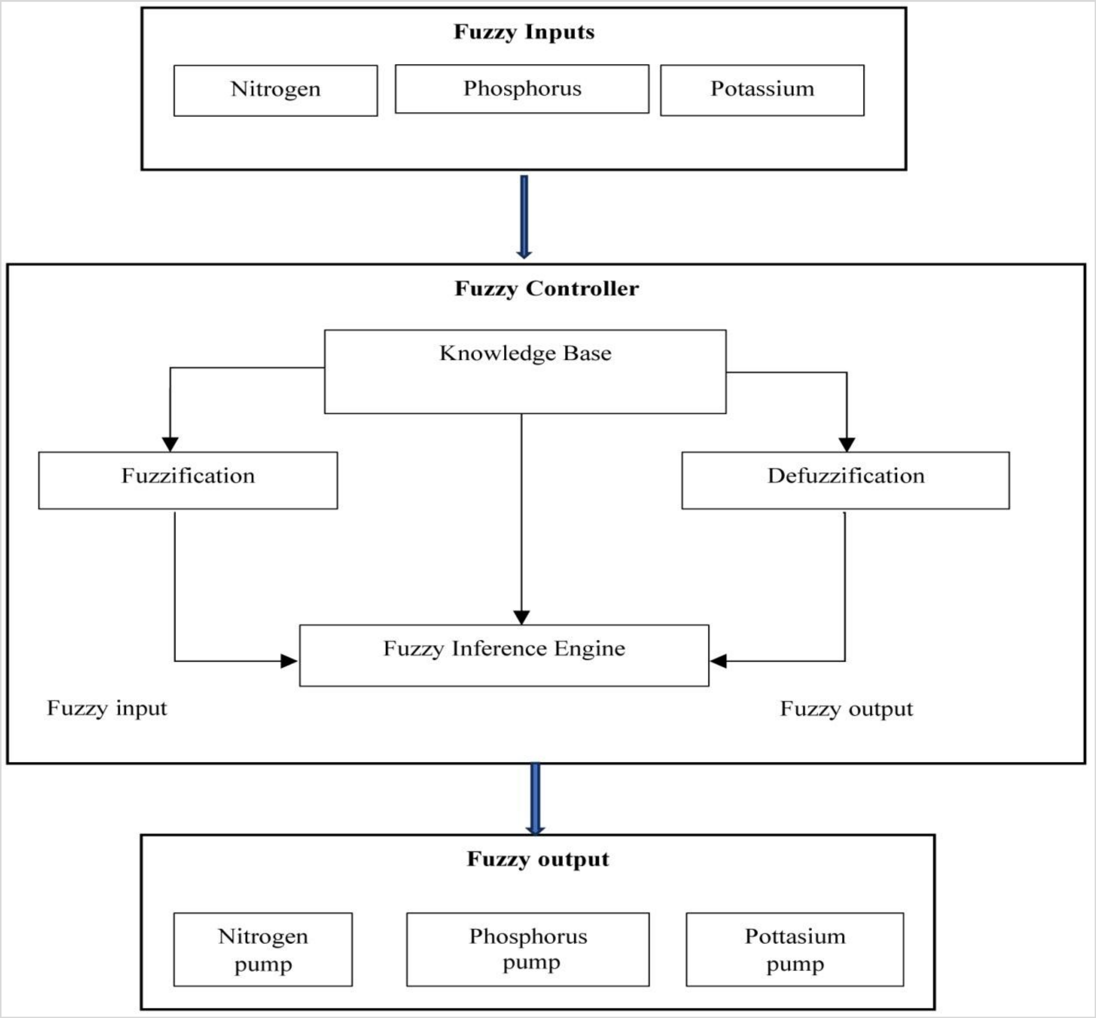


Figure 10 Fertilization fuzzy inference system

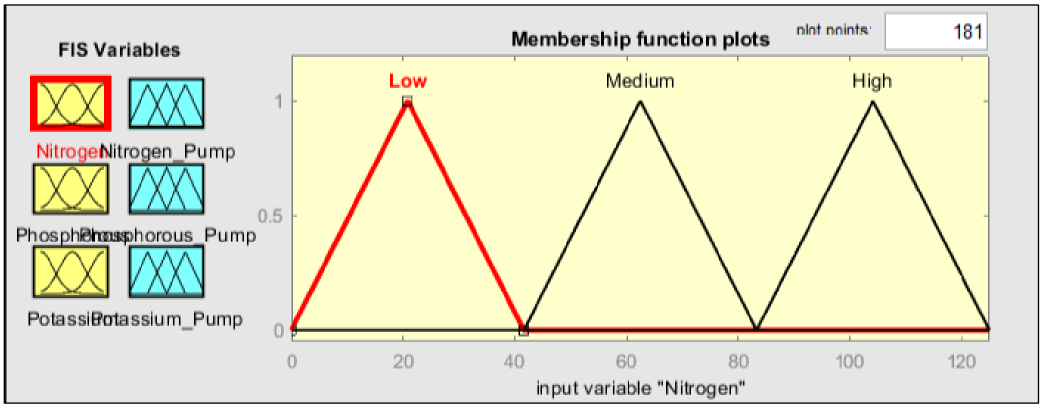


Figure 11 Membership function for nitrogen sensor

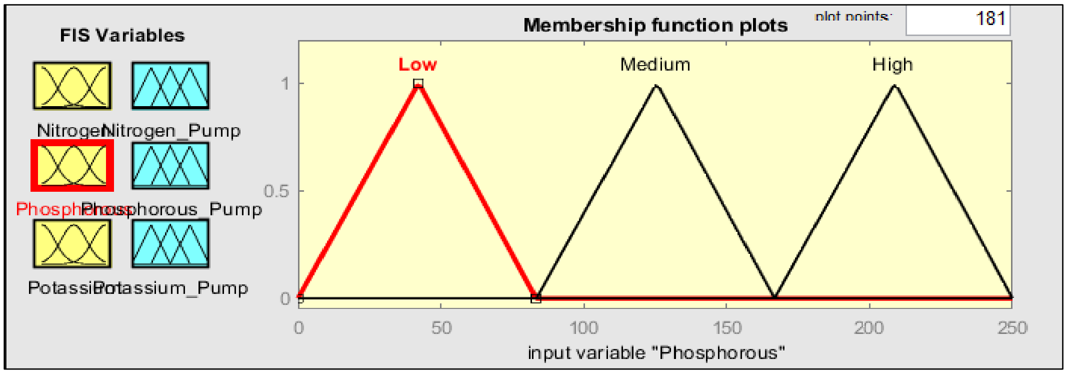


Figure 12 Membership function for phosphorous sensor

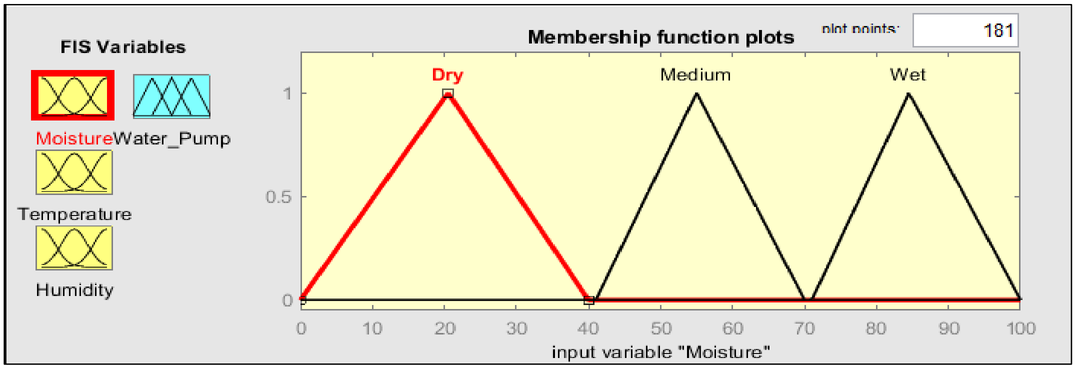


Figure 13 Membership function for potassium sensor

Table 4 Input variable sensor using mamdani method for fertilization

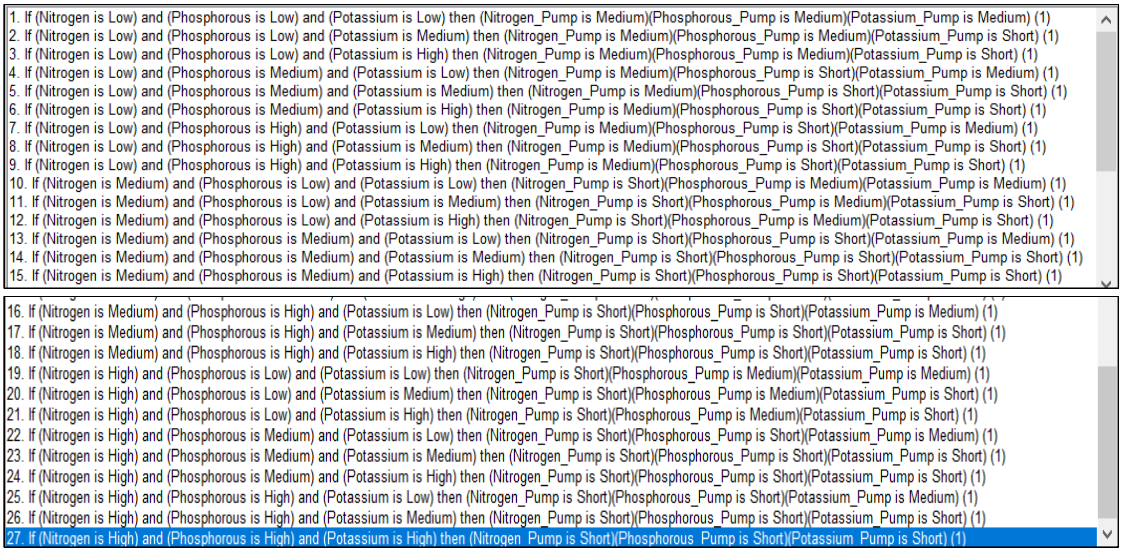
Sensor	Name of MF	MF Type	Range	Parameters
Nitrogen	Low	Triangular	(0, 125)	(0, 20.83, 41.66)
	Medium	Triangular	(0, 125)	(41.66, 62.5, 83.34)
	High	Triangular	(0, 125)	(83.34, 104.2, 125)
Phosphorous	Low	Triangular	(0, 250)	(0, 42.16, 83.33)
	Medium	Triangular	(0, 250)	(83.33, 125.5, 166.7)
	High	Triangular	(0, 250)	(166.7, 208.8, 250)
Potassium	Low	Triangular	(0, 125)	(0, 20.83, 41.66)
	Medium	Triangular	(0, 125)	(41.66, 62.5, 83.34)
	High	Triangular	(0, 125)	(83.34, 104.2, 125)

3.9Leafy phase and fruit phase

Nitrogen (N) ensures good plant growth. Hence, the NPK fertilizer ratios for the leafy phase are 2-1-1. Meanwhile in the Fruit Phase, Potassium (K) aids in the growth of flowers and fruits. The NPK fertilizer ratios are therefore 1-1-2 for the fruit phase. Thus, the membership function and input description will be regulated to the stated ratio accordingly.

3.10Knowledge base rule

There are three different linguistic domains for each of the system's three input variables. Therefore, there are $3^3 = 27$ rules for the input parameters. For the fertilization system, the fuzzy logic rules are shown in *Figure 14.* Similar to the irrigation system, the rules were created using the Mamdani technique, and the simulation was performed using MATLAB. The fuzzy inference will collect and analyze the crisp input data, such as nitrogen, phosphorous, and potassium, using an interference rule base. Furthermore, these IF-THEN rules were applied for all phases of plant growth. *Figure 15* illustrates the fuzzy logic controller of the fertilization system using Mamdani method. Also, the controller was the same for all phases of plant growth.



1. If (Nitrogen is Low) and (Phosphorous is Low) and (Potassium is Low) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Medium)(Potassium_Pump is Medium) (1)
2. If (Nitrogen is Low) and (Phosphorous is Low) and (Potassium is Medium) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Medium)(Potassium_Pump is Short) (1)
3. If (Nitrogen is Low) and (Phosphorous is Low) and (Potassium is High) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Medium)(Potassium_Pump is Short) (1)
4. If (Nitrogen is Low) and (Phosphorous is Medium) and (Potassium is Low) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Short)(Potassium_Pump is Medium) (1)
5. If (Nitrogen is Low) and (Phosphorous is Medium) and (Potassium is Medium) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
6. If (Nitrogen is Low) and (Phosphorous is Medium) and (Potassium is High) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
7. If (Nitrogen is Low) and (Phosphorous is High) and (Potassium is Low) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Short)(Potassium_Pump is Medium) (1)
8. If (Nitrogen is Low) and (Phosphorous is High) and (Potassium is Medium) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
9. If (Nitrogen is Low) and (Phosphorous is High) and (Potassium is High) then (Nitrogen_Pump is Medium)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
10. If (Nitrogen is Medium) and (Phosphorous is Low) and (Potassium is Low) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Medium)(Potassium_Pump is Medium) (1)
11. If (Nitrogen is Medium) and (Phosphorous is Low) and (Potassium is Medium) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Medium)(Potassium_Pump is Short) (1)
12. If (Nitrogen is Medium) and (Phosphorous is Low) and (Potassium is High) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Medium)(Potassium_Pump is Short) (1)
13. If (Nitrogen is Medium) and (Phosphorous is Medium) and (Potassium is Low) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Medium) (1)
14. If (Nitrogen is Medium) and (Phosphorous is Medium) and (Potassium is Medium) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
15. If (Nitrogen is Medium) and (Phosphorous is Medium) and (Potassium is High) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
16. If (Nitrogen is Medium) and (Phosphorous is High) and (Potassium is Low) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Medium) (1)
17. If (Nitrogen is Medium) and (Phosphorous is High) and (Potassium is Medium) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
18. If (Nitrogen is Medium) and (Phosphorous is High) and (Potassium is High) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
19. If (Nitrogen is High) and (Phosphorous is Low) and (Potassium is Low) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Medium)(Potassium_Pump is Medium) (1)
20. If (Nitrogen is High) and (Phosphorous is Low) and (Potassium is Medium) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Medium)(Potassium_Pump is Short) (1)
21. If (Nitrogen is High) and (Phosphorous is Low) and (Potassium is High) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Medium)(Potassium_Pump is Short) (1)
22. If (Nitrogen is High) and (Phosphorous is Medium) and (Potassium is Low) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Medium) (1)
23. If (Nitrogen is High) and (Phosphorous is Medium) and (Potassium is Medium) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
24. If (Nitrogen is High) and (Phosphorous is Medium) and (Potassium is High) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
25. If (Nitrogen is High) and (Phosphorous is High) and (Potassium is Low) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Medium) (1)
26. If (Nitrogen is High) and (Phosphorous is High) and (Potassium is Medium) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)
27. If (Nitrogen is High) and (Phosphorous is High) and (Potassium is High) then (Nitrogen_Pump is Short)(Phosphorous_Pump is Short)(Potassium_Pump is Short) (1)

Figure 14 Fertilization IF-THEN rules

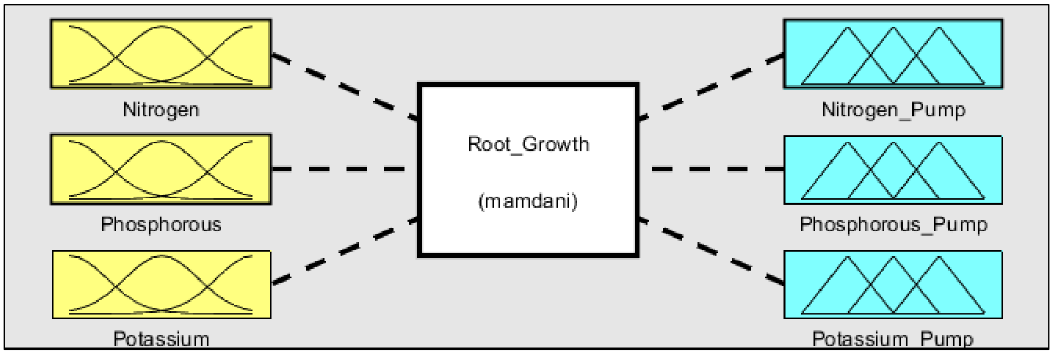


Figure 15 Fuzzy logic controller of the fertilization system using mamdani method

3.11Defuzzification and crisp output

Just like the defuzzification process in irrigation system, the crisp value supposedly to be fed to the controller is created by defuzzifying the fuzzy output of the fuzzy inference engine. The membership function's parameters were uniform for all phases of plant growth. *Figures 16*, *17*, and *18* illustrate the membership function for nitrogen, phosphorus, and potassium pump rate respectively, while *Table 5* lists the input variables for each of them.

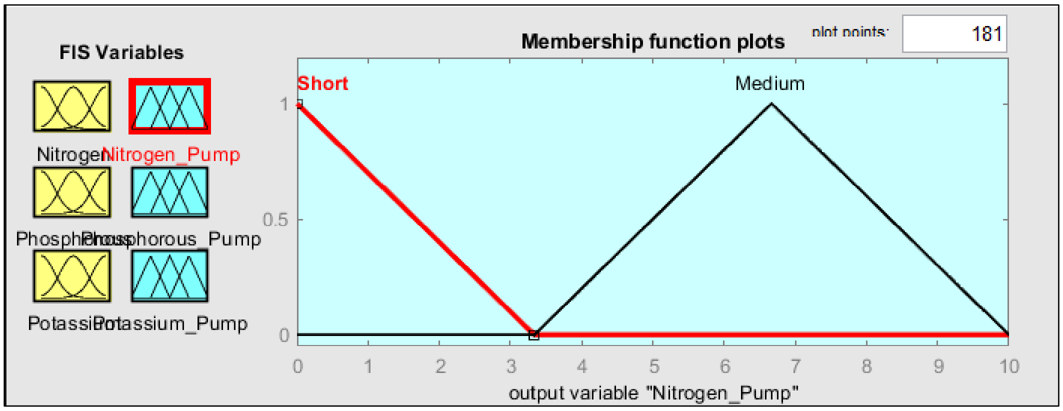


Figure 16 Membership function for nitrogen pump rate

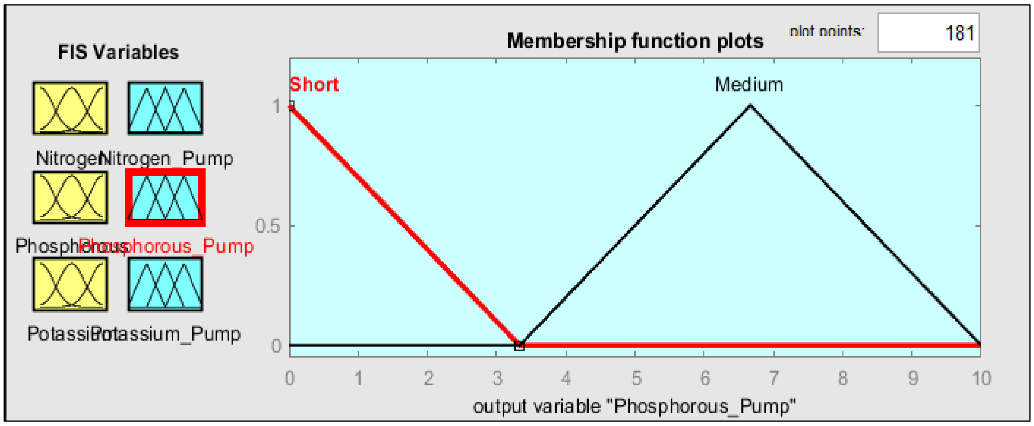


Figure 17 Membership function for phosphorous pump rate

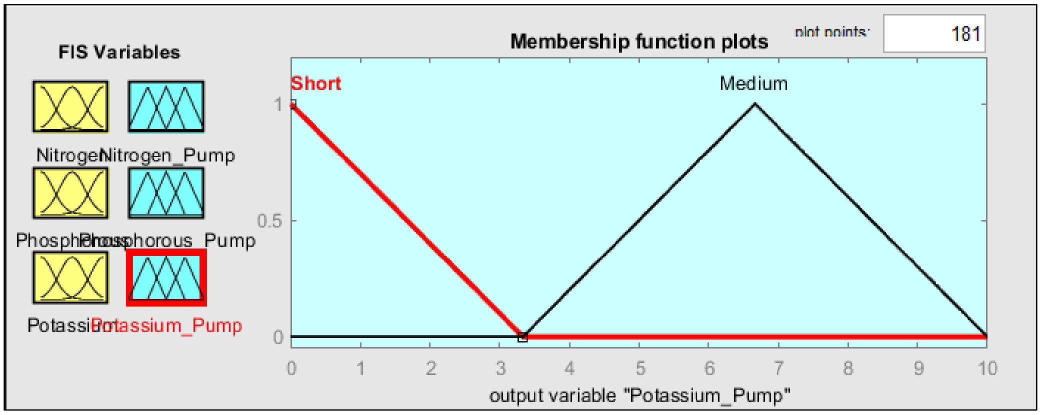


Figure 18 Membership function for potassium pump rate

Table 5 Input variable of using mamdani method for nitrogen, phosphorus and potassium pump

Sensor	Name of MF	MF Type	Range	Parameters
Nitrogen Pump	Short	Triangular	(0, 10)	(-3.33, 0, 3.33)
	Medium	Triangular	(0, 10)	(3.33, 6.67, 10)
Phosphorous Pump	Short	Triangular	(0, 10)	(-3.33, 0, 3.33)
	Medium	Triangular	(0, 10)	(3.33, 6.67, 10)
Potassium Pump	Short	Triangular	(0, 10)	(-3.33, 0, 3.33)
	Medium	Triangular	(0, 10)	(3.33, 6.67, 10)

3.12Use case diagram of C-farm application

The use case diagram for the C-Farm mobile application is shown in *Figure 19*. A use case diagram can be used to summarize details about the users and the fertigation system. From the Figure, the sensor data, water use, and NPK fertilizer usage are all presented in the C-Farm application, allowing farmers to monitor their plants. All the data will be retrieved from the cloud firestore database [39]. The farmer has access to monthly water and NPK fertilizer usage as well as previous sensor data in addition to the most recent data. In the C-Farm application, the farmers may also view weather forecast data that is retrieved from the weather application programming interface (API) and details about the NPK fertilizer ratios based on the stage of plant growth. This section discusses fuzzy reasoning rules and is divided into two, one for irrigation and another for fertilization. The fuzzy reasoning rule is appropriate for evaluating the precision of the membership function that was completed within earlier stage. Some input is necessary to be supplied for assessing fuzzy logic reasoning module.

3.13Irrigation

Figure 20 shows the fuzzy reasoning rule table for the irrigation system when including the value of input using the Mamdani method. The output value, the water pump rate is produced by adding an input value of 63.4 for soil moisture, a value of 56.9 Celsius for humidity, and a value of 29.7 Celsius for temperature. A crisp output is generated at a water pump rate of 2.44 seconds based on these provided inputs.

3.14Fertilization

Figure 21 demonstrates the fuzzy reasoning rule table for the fertilization system when including the value of input using the Mamdani method. This fuzzy reasoning rule table was for the root phase and used 1-2-1 NPK fertilizer ratios. Combining input values of 78 for nitrogen, 65 for phosphorus, and 59 for potassium yielded three output values: nitrogen pump rate, phosphorous pump rate, and potassium pump rate. The crisp output is generated at a nitrogen pump rate of 1.44 seconds, a phosphorous pump rate of 6.67 seconds, and a potassium pump rate of 1.44 seconds.

3.15Usability assessment and user feedback

The evaluation of the proposed system included a comprehensive assessment of usability, user-friendliness, and overall system performance. This process involved the application of user testing and feedback collection methods, making sure that the system is effective in real-world usage scenarios. These methods play their part in gathering invaluable insights into the system's usability and its alignment with end-users' needs and expectations. The findings from these usability assessments and user feedback highlighted several positive aspects of the smart fertigation system with mobile application and fuzzy logic optimization. Users appreciated the system's intuitive design, which facilitated seamless navigation and task completion. The real-time data presentation, including soil moisture, temperature, and humidity, was deemed informative and beneficial for making informed decisions regarding irrigation and fertilization. Despite that, there are some areas that need to be improved according to the feedback. Some users suggested enhancing the accessibility of certain features, optimizing the mobile application for different device types, and refining the visualization of analytical data. Their input was invaluable in guiding future refinements of the system. In summary, the integration of user testing and feedback collection methods played a pivotal role in the evaluation of the system's usability. These insights do not only provide validation of the system's effectiveness but also directed us toward refinements and enhancements that will further optimize the user experience. The user-centric approach to assessment ensures that the Smart fertigation system with mobile application and fuzzy logic optimization is not only technologically advanced but also aligned with the practical needs and expectations of its end-users in agricultural settings.

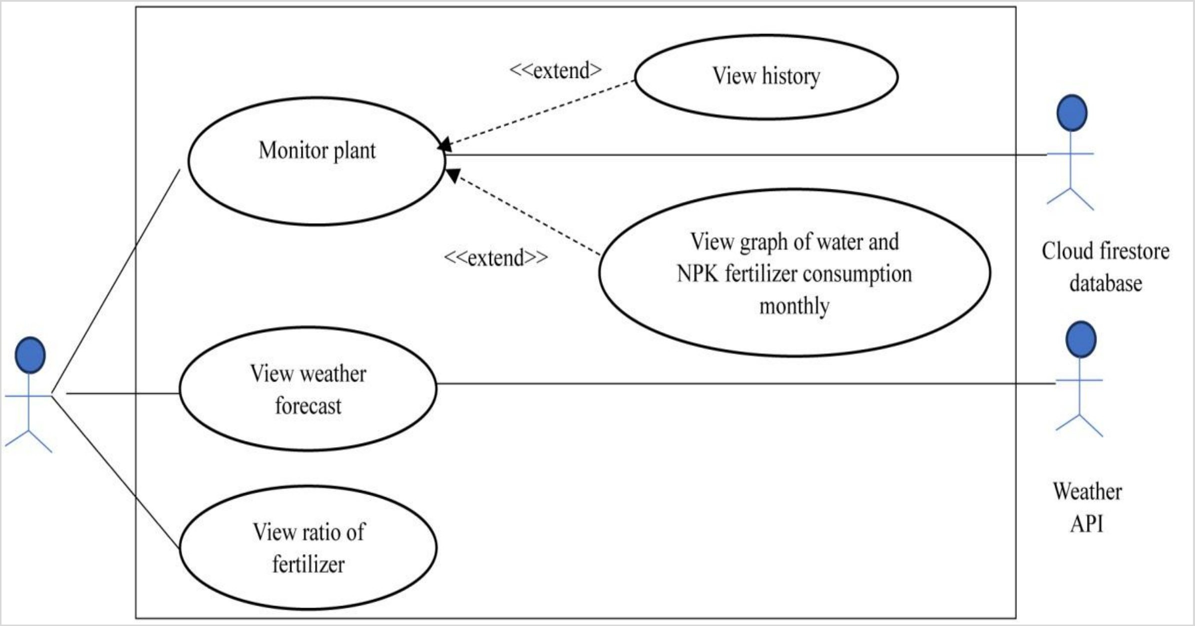
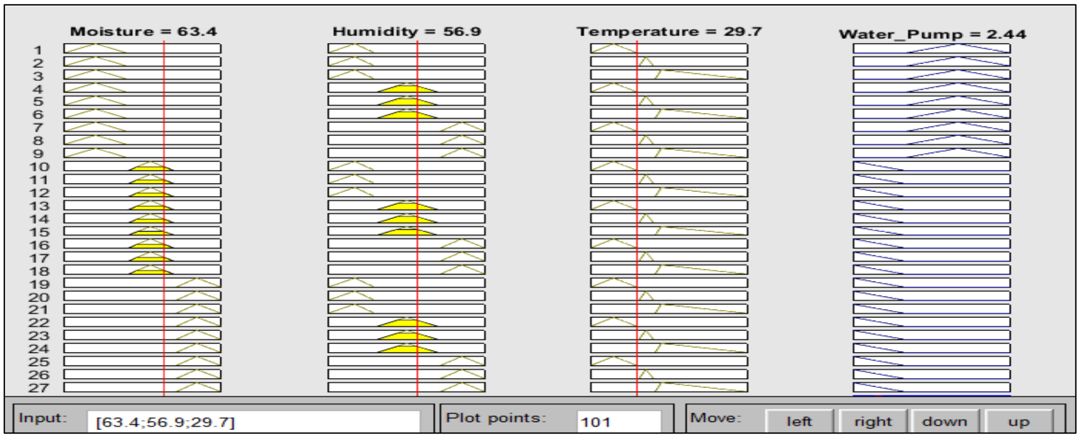


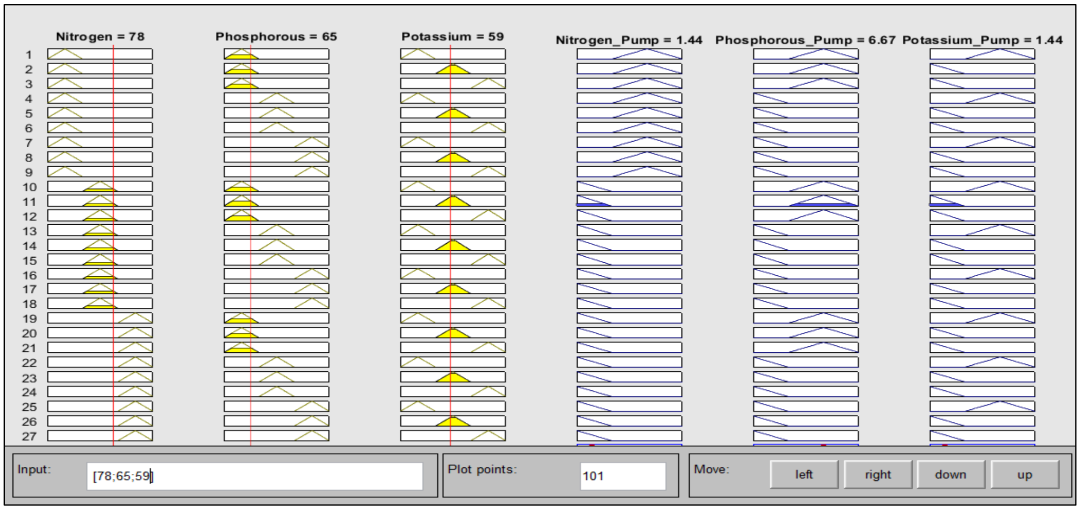
Figure 19 Use case diagram



Input: [63.4;56.9;29.7]

Plot points: 101

Figure 20 Irrigation fuzzy reasoning rule from MATLAB



Input: [78;65;59]

Plot points: 101

Figure 21 Fertilization fuzzy reasoning rule from MATLAB

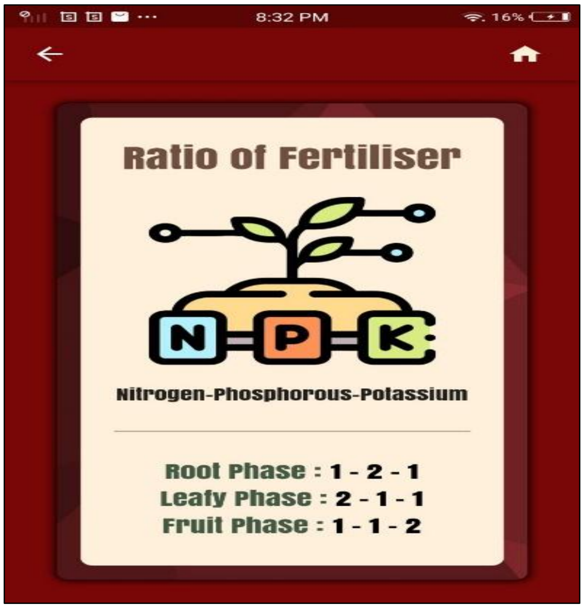
4.Results

In this section, we present the outcomes of our study, offering a detailed examination of the performance and efficacy of the proposed smart fertigation system with mobile application and fuzzy logic optimization. The results are delineated through two main subsections: remote monitoring system and testing evaluation.

4.1Remote monitoring system

Figure 22 shows the interface of the C-farm ratio of fertilizer page. Information like the NPK fertilizer ratio based on the stage of plant growth can be viewed on this page. The ratio of fertilizer for the root phase, leafy phase, and fruit phase are 1-2-1, 2-1-1, and 1-1-2 respectively. There is also a “Home” icon on the application bar which led the user back to the home page.

Figure 23 shows the page for the chili plant monitoring. As for this figure, these are the chili plants in Section 1. The information is divided into two parts which are irrigation system and fertigation system. In the irrigation part, the data includes the last watered status, including day, date, and time with the volume of water used for the irrigation. It also displays the soil moisture, temperature, and humidity value. In the fertilization part, the data includes the day, date, and time of the most recent fertilization as well as the amount of NPK fertilizer used. The values for nitrogen, phosphorus, and potassium are also shown. Both irrigation and fertigation part will display the latest data that are retrieved from the cloud firestore database. Additionally, the info icon in the fertilization part displays a popup message regarding the NPK fertilizer ratio. On the right side of the application bar, there are three different icons. The analytics icon is the first icon to the right that leads user to the analytics page, while the history icon, the second icon to the right leads user to the history page.



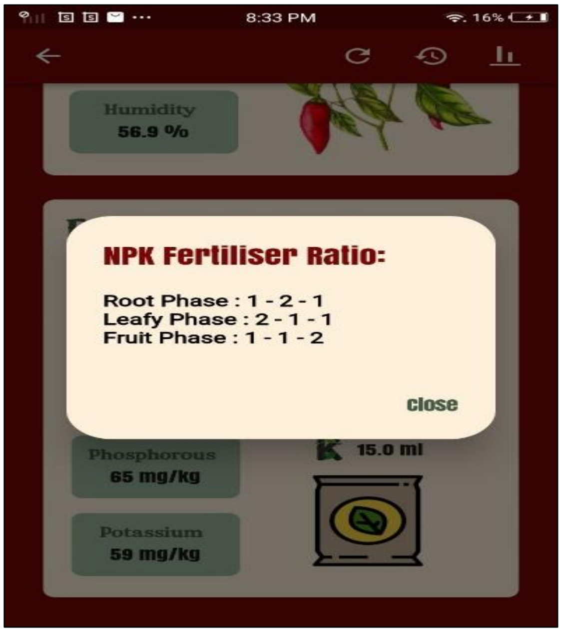
Ratio of Fertiliser

Nitrogen-Phosphorous-Potassium

Root Phase : 1 - 2 - 1
Leafy Phase : 2 - 1 - 1
Fruit Phase : 1 - 1 - 2

Figure 22 C-Farm ratio of fertilizer page

Figure 24 shows the interface of C-Farm analytics page. The user will be directed to the analytics page after clicking the analytics icon. On display, there will be a bar graph showing monthly water and NPK fertilizers usage. The graph can be scrolled to the right to view the previous month.



Humidity
56.9 %

NPK Fertiliser Ratio:

Root Phase : 1 - 2 - 1
Leafy Phase : 2 - 1 - 1
Fruit Phase : 1 - 1 - 2

Phosphorous
65 mg/kg

15.0 ml

Potassium
59 mg/kg

Figure 23 C-farm plant monitoring page

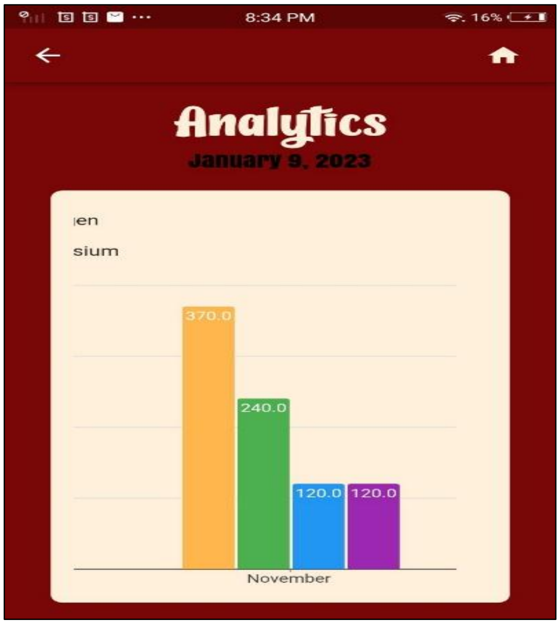


Figure 24 C-farm analytics page

4.2Testing evaluation

For the purpose of instructing the water pump for optimizing the water distribution across the farm, the system makes use of input variables including soil moisture, humidity, and temperature in an effort to increase the irrigation system's efficiency and reliability. The system's three inputs will be used to determine the irrigation output. In terms of fertilization, the nitrogen pump, phosphorous pump, and potassium pump are each controlled by input variables like nitrogen, phosphorous, and potassium. The system will calculate the fertilization output using the three inputs. Both irrigation and fertilization system output are summarized in the respective *Table 6* and *Table 7*, based on the data gathered. Specific to fertilization, the data were collected when the chili plant was at its root phase.

The smart fertigation system with mobile application and fuzzy logic optimization represents a significant enhancement of existing automated fertigation systems. A meticulously designed hardware setup ensures the system's reliability, underscoring the importance of selecting appropriate hardware and software components to construct an effective and successful system. The integration of a fuzzy logic algorithm further augments the system's efficiency. Additionally, the inclusion of a mobile application empowers agricultural business owners with the ability to remotely monitor and manage their farms, contributing to improved overall operational control.

4.2.1Validation of the fuzzy logic algorithm

The fuzzy logic algorithm validation process was rigorous and thorough. It commenced with the meticulous collection of real-time data, serving as the foundation for creating precise fuzzy logic rules that governed irrigation and fertilization recommendations. The dataset included vital parameters such as soil moisture, temperature, humidity, nitrogen, phosphorous and potassium. Following rule-based design, a comprehensive set of fuzzy logic rules was established, expertly mapping input variables to irrigation and fertilization recommendations. This granular approach ensured tailored responses to the dynamic needs of cultivated plants, highlighting the adaptability of fuzzy logic, which excels in managing the inherent uncertainty in agricultural systems.

Extensive simulation testing simulated various environmental conditions and growth stages, replicating real-world variability. The algorithm's responsiveness and adaptability were evaluated, demonstrating its readiness for practical agricultural applications. Furthermore, a direct comparison with traditional methods confirmed the algorithm's superior performance in optimizing water and nutrient delivery, establishing it as a key component within the smart fertigation system with mobile application and fuzzy logic optimization.

Table 6 Irrigation testing data

Soil moisture (%)	Temperature(^{o}C)	Humidity (%)	Water Pump(ml)
63.4	29.7	56.9	48.8
58.7	29.5	39	48.4
63.4	29.7	56.9	48.8
75.3	27.9	56.9	45.8
51	26.9	70	150
49.8	26.6	59	43.8
51.3	27.7	69	48
36.5	26.4	76	200
65.2	26.9	76	44.2
63.4	29.7	56.9	48.8

Table 7 Fertilization testing data

Nutrient in soil (mg/kg)			**Pump (ml)**		
Nitrogen	Phosphorous	Potassium	Nitrogen	Phosphorous	Potassium
78	65	59	28.8	133.4	28.8
56	69	73	27.4	133.4	27.4
74	63	55	26	133.4	26
68	79	43	31.8	133.4	31.8
53	49	62	24.8	133.4	24.8
61	47	52	25.4	133.4	25.4
60	55	63	23.4	133.4	23.4
61	65	69	26.2	133.4	26.2
82	78	79	31.8	133.4	31.8
78	65	59	28.8	133.4	28.8

4.2.2Hardware component testing

Hardware component testing was a critical phase of the evaluation process, ensuring the reliability and functionality of the fertigation system. It encompassed some key elements such as functional testing, integration testing, and long-term reliability testing.

Functional testing: Every hardware component, which includes sensors, pumps, and controllers, underwent comprehensive functional testing. This rigorous examination was done to make sure that each component is reliable and accurate during its operation across a diverse range of conditions.

Integration testing: Our evaluation also focused on the interaction and compatibility of hardware components within the system. This meticulous examination identified and resolved potential integration issues, ensuring the seamless operation of the system as a whole.

Long-term reliability testing: To assess the durability and long-term reliability of the hardware components, they were subjected to extended periods of operation and data collection. This phase of testing was important to ensure that the components are able to perform consistently over an extended duration.

4.2.3Accuracy and performance metrics

To measure the accuracy and performance of the fuzzy logic algorithm and the hardware components, we established a range of specific metrics:

Accuracy in irrigation and fertilization: Metrics such as precise water distribution and optimal nutrient supply were employed to assess the accuracy of the system's recommendations. This ensures that delivery of the right amount of water and nutrients to the plants are done consistently by the system.

Energy efficiency: Energy consumption of the hardware components was systematically recorded and analyzed. This approach ensured that the system operates efficiently, while minimizing the use of energy as it maintains optimal functionality.

Reliability and stability: The system's overall reliability and stability were assessed through continuous operation and performance monitoring. This aspect of testing was crucial in determining the system's ability to maintain consistent performance over time.

In short, through rigorous validation and testing, we have confirmed the Smart fertigation system with mobile application and fuzzy logic optimization's reliability and robustness to be used in the real-world agricultural field. The system consistently delivers precise recommendations for irrigation and fertilization, and the hardware components seamlessly integrate, making it durable in long-term. The fuzzy logic algorithm shows adaptability and accuracy, while a set of key metrics ensures high performance standards, positioning our system as a reliable, efficient, and effective solution for modern agriculture.

5.Discussion

The integration of the Smart fertigation system with mobile application and fuzzy logic optimization portrays a significant advancement in modern agriculture, exemplifying the potential of technology in enhancing crop management and utilizing resource. Several key aspects require further consideration and reflection.

Efficiency of irrigation and fertilization processes: The incorporation of IoT sensors and fuzzy logic optimization has significantly improved the efficiency of both irrigation and fertilization processes. Real-time data from the sensors and the application's intelligent algorithms collaboratively fine-tune these processes, guaranteeing that the crops receive the precise amount of water and nutrients they require. As a result, it minimizes resource wastage and overcomes the challenges of under or over-irrigation and fertilization, thus, improving crop health and productivity.

Resource optimization: The system's dynamic adjustments based on environmental variables and crop requirements mark a substantial step forward in resource optimization. As an example, the integration of rain prediction data allows for intelligent water management, reducing over-irrigation and conserving water resources. Similarly, the tailored fertilization process ensures that nutrients are applied precisely, mitigating over-fertilization and its associated environmental consequences. This, in essence, promotes to sustainable farming practices and economic savings.

Improved crop yield and quality: The system helps to improve crop yield and quality through precise control over irrigation and fertilization. By providing crops with the right amount of nutrients and water at the right time, it helps maximize their growth potential and resilience to adverse environmental conditions. Not only does it enhance the overall yield, but it also ensures the high quality of the crops, meeting market standards and consumer preferences.

Real-time monitoring and decision support: The mobile application's role as a real-time monitoring tool plays a crucial role. As it provides farmers with continuous access to critical data, the application empowers timely decision-making and intervention. With this level of control, it can lessen the risks associated with suboptimal environmental conditions and enable proactive responses to plant health concerns.

Potential environmental and economic impact: The Smart fertigation system with mobile application and fuzzy logic optimization offers substantial potential, not only in terms of environmental, but also economic impact.

Environmental impact: By reducing over-irrigation and over-fertilization, the system helps in sustainability and water conservation. It helps reducing the environmental consequences of excessive resource usage, such as nutrient runoff and water wastage. Moreover, the real-time monitoring and predictive capabilities of the system allow for the early detection of potential issues, enabling more targeted interventions and minimizing environmental damage.

Economic impact: The system contributes to cost savings in agriculture by optimizing resource utilization and improving crop yield and quality. This situation increases revenue for farmers since they are able to achieve higher crop production with reduced input costs. Additionally, it reduces the risk of crop failure since the crops are able to adapt to changing environmental conditions, thus protecting the investment done by the farmers.

Comparison with existing fertigation systems:
In the context of existing fertigation systems, it's important to acknowledge the limits of only utilizing traditional methods and partially automated systems. Traditional fertigation methods often rely heavily on human labour, requiring the farmers' constant presence to monitor and manage the crops. This manual approach does not only lead to inefficiencies, but also leads to human errors, and difficulties in maintaining precision, especially in large-scale farming operations. While some partially automated systems have been proposed, a continuous key issue was the reliance on farmers' decisions to manage the fertilization. This introduces a degree of subjectivity and may result in less accurate application of water and fertilizer to crops, potentially leading to issues of over-fertilization or under-fertilization. The shortcomings of these existing systems drive the development of the proposed smart fertigation system, designed to address these challenges and usher in a new era of automation and precision in fertigation. The system integrates IoT technology, a user-friendly mobile application for real-time monitoring, and innovative fuzzy logic decision-making processes to optimize water and fertilizer application based on the growth phase of the plants. This approach represents a significant leap towards a fully automated and highly precise fertigation system, enhancing both the efficiency of crop management and the quality of the crops produced, particularly benefiting large-scale bird's eye chili growers.

The study has limitations that warrant consideration. One limitation lies in the need for comprehensive calibration and validation of the fuzzy logic optimization to ensure the accuracy of the system's outcomes. Rigorous testing and calibration are essential to guarantee that the system consistently delivers the expected results. Another limitation is the adaptability of the system to various crops and their different growth stages. This necessitates parameter adjustments and experimentation to guarantee the system's effectiveness when applied to a wide range of crops, ensuring optimal performance under different conditions. Given the unique requirements and growth patterns of different crops, meticulous fine-tuning is essential to meet these diverse needs effectively. Furthermore, integrating data from various sources, such as local weather stations, holds the potential to enhance predictive accuracy and refine decision-making. Addressing these limitations presents an opportunity to maximize the system's utility and ensure its applicability across a broad spectrum of agricultural settings. A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

Agriculture is a vital industry that provides the world's necessity of food. To improve agriculture practices, it is essential to monitor crops, and the Smart fertigation system with mobile application and fuzzy logic optimization is developed to assist farmers. The system uses the IoT and mobile application to reduce labor costs and time, and fuzzy logic to improve precision in plant irrigation and fertilization, resulting in better crop yield and quality. As a future work, the Smart Fertigation System can be further improved by adding a function to notify farmers of pump malfunctions through the mobile application, integrating rain prediction into the irrigation system, and using raspberry pi instead of NodeMCU as an intermediary to connect directly to the cloud firestore database, thus can reduce the hardware complexity.

In conclusion, the convergence of technology and agriculture finds a remarkable expression in the Smart fertigation system with mobile application and fuzzy logic optimization. This innovative integration has the potential to reshape traditional farming practices and enhance agricultural outcomes. Through the utilization of IoT sensors and a user-centric mobile application, the system simplifies complex farming tasks and introduces a new level of control and insight for farmers. The incorporation of fuzzy logic algorithms adds a layer of sophistication, enabling precise and adaptive management of irrigation and fertilization processes, thereby promoting resource efficiency and optimal crop yield. Looking ahead, a roadmap of promising future developments emerges to amplify the system's capabilities and impact. The introduction of a pump malfunction alert mechanism within the mobile application ensures timely responses to technical glitches, safeguarding crops from potential damage. Apart from that, by incorporating predictive rain forecasts into the system's decision-making process, irrigation can be intelligently adjusted to account for impending weather conditions, thus conserving water resources while maintaining crop health. Furthermore, the transition from NodeMCU to raspberry pi for cloud connectivity holds the promise of enhanced data processing power and seamless communication, reducing hardware complexity and increasing reliability. This transition enables the system to handle more complex algorithms and analyses, facilitating smarter and more informed agricultural management.

To cater to the diverse needs of farmers and crops, an expansion of the system's adaptability to different plant species and growth stages would broaden its application and utility. Customizable algorithms could provide tailored recommendations, optimizing the system's effectiveness across various agricultural scenarios.

In essence, the Smart Fertigation System's journey is a testament to the ongoing pursuit of precision and sustainability in agriculture. The envisioned enhancements collectively chart a course toward an agricultural landscape characterized by efficient resource utilization, improved yield, and technological sophistication, ensuring a brighter and more secure future for global food production.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Nurul Anis Zulaikha Izahar: Investigation, development, testing, analysis, writing, and editing. **Mohd Noor Derahman:** Idea generation, data validation, correction, study conception, design, data collection, supervision, and overall project coordination. **Mohamad Afendee Mohamed:** Editing, manuscript testing, manuscript preparation, data validation, feedback, project support and technical content review. **Imas Sukaesih Sitanggang:** Editing, manuscript testing, manuscript preparation, research coordination data validation, feedback, data analysis support.

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Appendix I

S. No.	Abbreviation	Description
1	AI	Artificial Intelligence
2	ANN	Artificial Neural Networks
3	API	Application Programming Interface
4	EC	Electrical Conductivity
5	IoT	Internet of Things
6	K	Phosphorus
7	LoRaWAN	Long Range Wide Area Network
8	ML	Machine Learning
9	N	Nitrogen
10	NPK	Nitrogen, Potassium, Phosphorus
11	P	Pottasium