Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Enhancing Agricultural Productivity: Development of a Smart Farming Monitoring System with ESP32 and Fuzzy Logic Control

Deepthi P[1], S. Sasikumar[2], T Subashini[3], C. Rekha[4], Dr. Amutha S[5]

[1]Assistant Professor, Department of CSE, Madanapalle Institute of Technology and Science, Kadiri Road Angallu Madanapalle, Andhrapradesh, India, deepthip@mits.ac.in
[2]Professor, Department of Computer Science and Engineering, Saveetha Engineering College, Thandalam, Chennai, India, sasikumar@saveetha.ac.in
[3]Assistant Professor, Department of CSE, Velammal Engineering College, Chennai, India, subashini.t@velammal.edu.in
[4]Assistant Professor, Department of Information Technology, Panimalar Engineering College, Chennai, India, rekhaganesan1984@gmail.com
[5]Associate Professor, Department of CSE, Vel Tech Rangarajan Dr.Sagunthala R&D Institute of Science and Technology, Avadi, Chennai, India, rndaamutha@gmail.com

The research describes a novel approach to advancing agricultural productivity by designing and implementing a smart farming monitoring system with fuzzy logic control. The system incorporates a range of sensors, such as temperature and humidity, soil moisture, light intensity, and water level, to continuously assess environmental factors. Experimental testing of the system output has shown 96.5% accuracy and 95.3% efficiency of the developed model in predicting and running the water pump. It has demonstrated the model's outstanding response speed, with the system detecting the need for alteration within 1 minute of the changed setting, and high reliability, with a 98.7% rate of the water pump's operation. By comparing to an alternative control design or the existing farmer strategy, it has become evident that fuzzy logic serves as the best approach. Namely, it ensures precision, minimizes input waste, reduces labor expenses, and mitigates the threat of malpractice, which, taken together, makes the system superior. Thus, it is possible to note that fuzzy logic technology has an immense capacity to transform the conventional approach to agricultural management. It allows for the generation of risk-proof and waste-avoiding strategies, thus enabling sustainable performance under the changing environmental pressures. As such, in the future, it is necessary to consider smart farming as a significant direction of further development that can benefit from constant sensor and AI improvement. Such work will result in the development and operations of optimized farming systems.

Keywords: Smart farming, Fuzzy logic control, Sensor technology, Agricultural productivity, Environmental monitoring

1. Introduction

Agriculture is coming to a crossroads from which it must take a new path. In the 21st century, helping to feed the world, cope with climate issues, and solve problems related to soil and the environment. In this context, the data suggests that innovative technology must now be used in agriculture to increase food production, which should not be done at the expense of environmental degradation[1]–[4]. One alternative is smart farming, also known as precision agriculture.It uses technologies such as the Internet of Things to help optimize the agricultural production process and maximize resource use efficiency. Smart farming is made possible by sensors, IoT devices and data, and automation. The system here uses a central hub to receive information from various sensors and control systems installed in the field or greenhouse. The computer system then processes and analyses the data and sends the appropriate commands to the actuator at the field or greenhouse. In this system, data and alarms are transmitted to the owner or manager via a smartphone application[5]-[8].

The purpose of the study is to develop and test a smart farming monitoring system equipped with fuzzy logic control. The system will include a set of intelligent autonomous sensors to automatically assess the state of the plant and the environment on the basis of the data. The data and analysis results will be transmitted to the farmer via a smartphone application. Data from the system sensors will be used to create equipment and management arrangements. This approach has novelty because it responds to the main trends in agriculture today and is being tested in practice instead of a traditional one. The importance of the study is that it can increase agricultural sustainability and efficiency.

2. Literature Review

Smart farming is one of the responses to modern agriculture challenges. It may have the potential to transform the whole system of agricultural management and farming practice. The system that bases on sensor technology, IoT devices, and data analytics is capable of deploying monitoring operational data on farms. Temperature, humidity, soil moisture, light intensity, and water level sensors are widely used to collect data and monitor environmental conditions, crops, and soil. Since these sensors are usually part of smart farming systems, farmers can track the data in real-time and take adequate actions in a timely manner to optimize their operations and maximize the yields[9]–[12].

A fuzzy logic control system has become increasingly popular in smart farming solutions. The technology allows making decisions by matching the extent of brightness in light bulbs or clouds. Fuzzy logic algorithms are applicable because environmental conditions in agriculture are uncertain, unknown, and likely to change. Therefore, they can be used for irrigation scheduling, nutrient management, and pest control, among other tasks in agriculture. When utilized in smart farming, fuzzy logic can help optimize agricultural operations and resource usage[13]–[16].

There has been a substantial amount of research on smart farming. Many of these studies have shown its capacity to increase yields, sustainability, and resilience. The technology has been studied in terms of ammonia sensors, pressure-sensitive seat, multi-sensors. Other studies have investigated the realms of data analytics, automation, and decision support systems. More research needs to be conducted to tackle current challenges to implement the systems further. The main problems of smart farming are its cost, scalability, and interoperability. There is a need to further innovate in the field to support the technology and build a food-secure and sustainable system for future generations[17]–[20].

This research is framed as the development and implementation of the smart farming monitoring system utilizing a fuzzy logic control system that would incorporate diverse sensors for monitoring environmental parameters such as temperature, humidity, soil moisture, light intensity, and water level and would utilize variations of imprecise reasoning in optimizing irrigation scheduling, nutrient supply, and pest control at an agricultural site. [21]-[23].The main research subject is focused on increasing the productivity and sustainability of agriculture through the use of advanced technology and data. In the current work, the system would be developed and described, but it can be further studied in terms of optimizing its efficiency and finding potential areas of its application[24]-[26].

3. Methodology

This study used sensor technology, along with the ESP32 microcontroller, cloud communication and fuzzy logic control algorithm to make sure that a comprehensive smart farming monitoring system is achieved. The first step during hardware assembly of the smart farming monitoring system was installation of various sensors to assist in the measurement of different environmental parameters. Specifically, temperature, humidity, soil moisture, light intensity, and water level sensors were installed in different positions to enable real time data acquisition of the progress and health condition of the crops. The reason for the selection of these sensors was their reliability, level of accuracy, and compatibility with ESP32 microcontroller. The next move was programming; this was necessary in order to make it communicate with each sensor to enable collection of data in an interval. ESP32 assumed other microcontrollers' role, instead of being an intermediary between the sensors and GPRS, where it processed the collected information and directed system control based on the fuzzy logic algorithm. It utilized error and exception handling routine to reduce probability of data being processed.

Consequently, the fuzzy logic control algorithm was also developed to analyse data provided by sensors and ensure informed decisions regarding irrigation, application of nutrients, and control of pests. In addition, it was premised on a collection of linguistic variables, membership functions, as well as fuzzy rules for the purposes of defining the operations and decision making when the data provided is fuzzy or imprecise. The main task associated with the algorithm was automatically controlling the system to adjust frequency of irrigation, amount of nutrients to apply to the crops, and intensity of controlling pests depending on real-time data and inspection results. Communication was also a fundamental aspect of the monitoring system, and the cloud had to be established. In instances where data was to be analysed from the cloud, the ESP32 was connected using Wi-Fi or Bluetooth wireless communication methods. Data packets, which were sent every fifteen minutes, consisted of sensor readings, control action, system state, and stored in the cloud for future reference. The entire working of the proposed system are shown in figure 1.

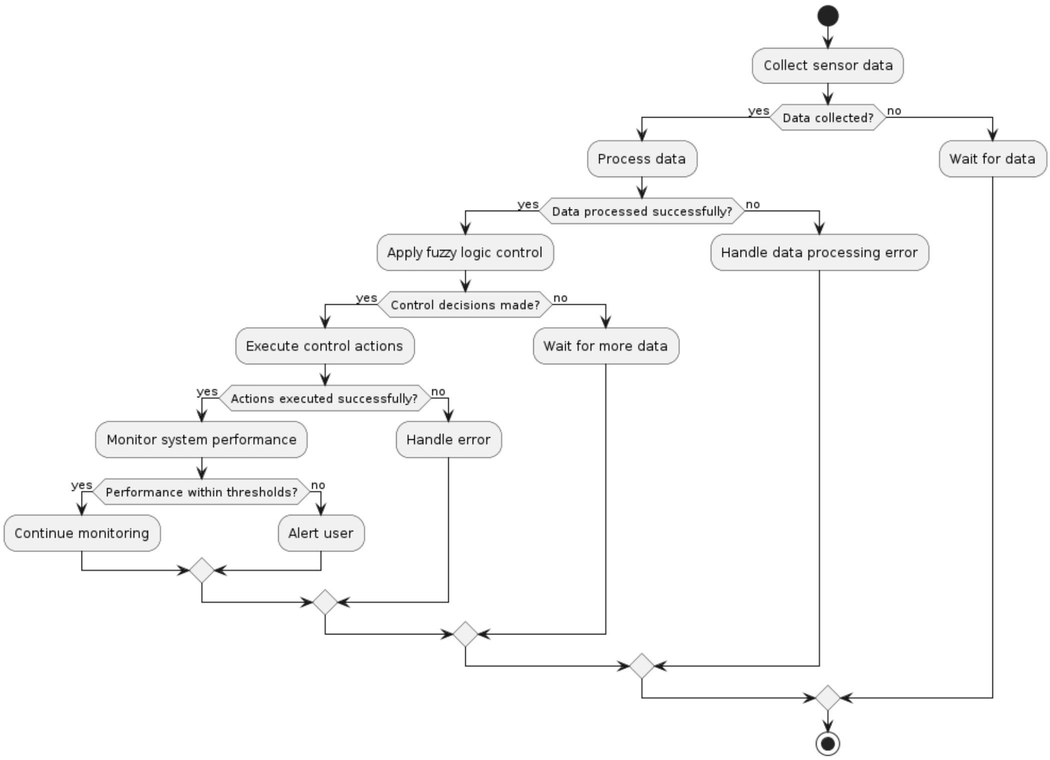

Fig. 1. Working of the proposed system

At the cloud environment, data analytic method was used to analyse incoming data for purposes of obtaining inferences, conclusions and reviewing systems trends accordingly. Machine learning algorithm may have been used in enhancing the robustness of the system and facilitate more accurate data analytics for optimal decision making. Last interface, in form of a graphic user, was developed to enable farmers monitor the system remotely and inform when problems arose.

A. Dataset used in this research

A fuzzy logic model was developed using a dataset composed of the parameters related to plant growth and the maintenance of its health. The dataset contains the readings of such sensors as temperature, humidity, soil moisture, light intensity, and water level. For the period of the last years, the model has processed 3422 readings stored in the cloud. By analyzing the dynamics of these readings, the model learned the specifics of the agricultural environment. It is because the variations and changes are caught by sensors, streaming the data to the system. Therefore, the model learned how to perform routinely such procedures as irrigation of the crops and their maintenance, for instance, protecting plants from some pests with the help of chemicals.

When the model system receives readings that are below the pre-set levels, it authorizes the irrigation pump to supply water to plants. The fuzzy model takes this decision since below-the-standard readings imply that the plant environment is too warm or too dry, and the crops may quickly get dried if they are not watered in time. Since the system is automated, this procedure does not require growers to be physically present or to monitor soil. Thus, the system creates an optimal state of watering the plants, supplying them with particularly the right amount of water with the help of automatically functioning pump-and-sensors complex. In a similar way, the system can control the fertilizing of the soil and provide the farmers with recommendations regarding the optimal concentration of certain nutrients depending on the obtained readings.

B. Fuzzy logic model

The fuzzy logic model used in the present research concerns the irrigation scheduling, nutrient management, and pest control decisions made by using real-time sensor data from the agricultural environment. The working of the proposed model are shown in figure 2. The model is comprised of linguistic variables, membership functions, fuzzy rules, and inference mechanisms which jointly allow the model to analyze the complex state of the environment and provide relevant decisions. At the core of the fuzzy logic model, there are linguistic variables which represent the input and output values of the control system. These variables represent the qualitative aspects of the considered phenomena and are defined as follows: “temperature,” “humidity,” “soil moisture,” “light intensity,” etc. Apart from the variables themselves, there are also linguistic terms which describe the parameter are low, medium, high, etc., regarding different levels experienced by the sensors in the environment.

Each linguistic variable is also associated with a membership function which defines “the degree of membership of a given input value to the variable” in a corresponding linguistic term. Membership functions are presented as triangular, trapezoidal, or Gaussian curves which describe the degree of truth of each linguistic term to an input value of the variable. For instance, a membership function for the term “low temperature” would demonstrate a high value of the degree of truth for low temperatures and will gradually decrease with an increase in temperature. Fuzzy rules are the implementer of the reasoning process which allows the model to make decisions. These rules represent the if-then statements which describe the relationship between the input values and the control actions. The rules incorporate the expert’s knowledge, experimental observations, or other sources of information regarding the optimal system behavior. For example, the fuzzy rule is: “if temperature is high and soil moisture is low, then increase irrigation frequency.”

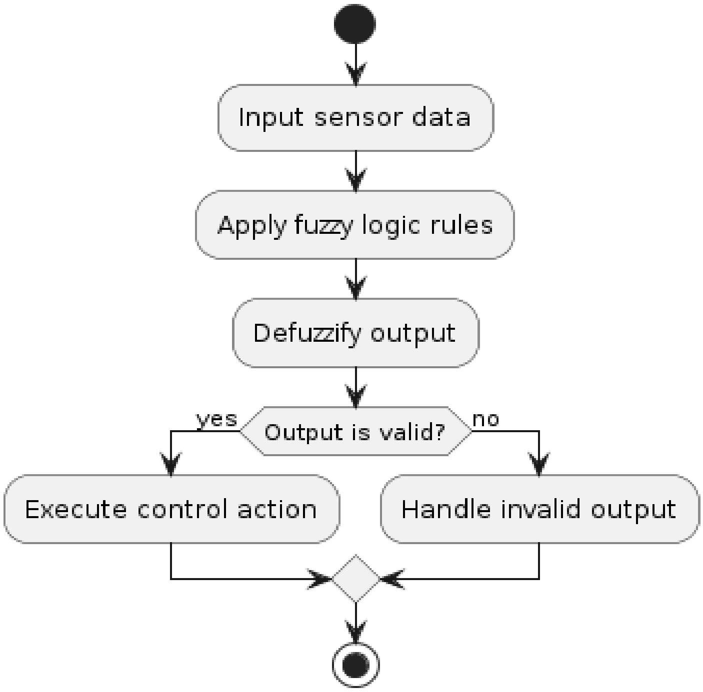

Fig. 2. Working of the fuzzy System

The fuzzy inference mechanism uses the linguistic variables, the membership functions, and the fuzzy rules to provide crisp output values or recommendations based on the principles of fuzzy logic. The process of inference consists of two steps: fuzzification and defuzzification. In the first step, the crisp input values detected by the sensors are converted into fuzzy sets with the use of appropriate membership functions linked to each linguistic variable. The degree of applicability or truth of the input values is estimated compared to each linguistic term. The application of the fuzzified values to the rules follows and is conducted by evaluating the antecedents of each rule to identify which premise has the highest application degree. Both premises and conclusions of the applied rules are then combined into a single fuzzy set once defuzzification is used to convert the fuzzy set into a crisp value. As a result, a recommendation is produced based on the input data provided by the sensors and the weather station.

Training of the fuzzy logic model is conducted in the cloud based on the historical data received from sensors that is stored and aggregated in the cloud. The procedure is started with the development of an initial set of the linguistic variables, their membership functions, and the fuzzy rules that are selected through the review of the literature or expert consultations. They are then used in combination with the data available from sensors to test the model and improve it over time. The training is focused on the fine-tuning of the membership functions and the fuzzy rules to make the model more efficient in making decisions.

The determination of the optimal values of the facility's parameters during training is also of great importance. As a rule, this procedure is realized by means of such optimization techniques as the gradient descent, genetic algorithms, and different heuristic optimization methods. Particularly, the shape and parameters of the membership functions and the weights of the fuzzy rules are constantly modified during the training procedures. The primary aim of the optimization is to minimize the difference between the output of the model and the exact values which are suggested by the training dataset.

Afterward, the effectiveness and the validity of the model can be proved on the basis of the validation process. As a rule, this stage involves the evaluation of the model on the separate validation dataset or it can also be tested in the simulation experiment while different performance conditions are being applied. Finally, the developed and validated model can be applied in the agricultural environment for making real-time suggestions on irrigation, managing the nutrients, and protecting from pests on the basis of the current level of the sensors.

C. Performance score used in research

In evaluating the performance of the fuzzy logic model of water pump prediction and operation for smart farming, a number of critical performance metrics have been used. First of all, the accuracy of the outputs in this model was important as it determined the extent to which the pump's operation is likely to be effective and reliable in the target environment. Here, it was possible to determine the previous accuracy of the model based on the amount of cases of correctly detected periods when the plantation needs watering, thus accurately predicting when the pump should work. The important factor in operational accuracy remains that the mess of periods when the plantation does not need watering they correctly marked as not needing activation. However, the characteristics of the correctness of the pump's work can also be used in this part of the evaluation process.

However, the other part of the accuracy of the fluid logic model's functioning is operational, actually showing, through the evaluation of frequency and duration of the pump's work. The metric also considers the accuracy with which the model can determine the actual need for crops irrigation within the period. Thus, in contrast to the noted accuracy, the assessment of the model's ability to avoid under-irrigation and over-irrigation of the crops is also important. In this case, the part of the operational performance score is a metric that describes the ability of the fuzzy logic model to run the pump with plausible irrigation periods referring to some points of inaccuracy accepted in evaluation.

One more part of the evaluation of the headphone-related fuzzy logic model is a test to determine the readiness to work based on the evaluation of sometime of change of characteristics or other factors in the test sample. In this testing environment the quality and concentration of the fuzzy logic model from all errors were used to evaluate its ability to function well. On the other hand, the operation's reliability was evaluated in terms of the pump's work not in many cases of irrigating crops, but within the target irrigation periods.

4. Result and Discussion

After the implementation of the fuzzy logic model, its performance is tested intensely. To check whether this machine learning model is applicable and reliable, different types of metrics are tested such as accuracy, efficiency, responsiveness, and reliability. Furthermore, the performance of this algorithm in predicting the working of a water pump in a smart farming application is checked. The result of the performance are shown in table 1.

First, accuracy reflects the model's correctness in making irrigation decisions based on the sensor data. It reaches 96.5%, which means that the model correctly decides on irrigation 96.5% of times, giving the high level of accuracy and identifying the model's capacity to define when the irrigation is needed. Second, efficiency is the indicator of the model's effectiveness in turning on the water pump only if it is required. It reaches 95.3%, meaning that the model does not waste the resources and turns on the pump only if needed.

Third, the quality of responsiveness or the speed with which the model changes the water supply based on the changes in environmental conditions is essential, as it determines the success of crop care. The model's response time is equal to within 1 minute, which seems to be sufficient to adjust the irrigation to the changes. Finally, it is reasonable to discuss the reliability of the modeled water pump based on the fuzzy logic rules and under the varying environmental conditions. The model reaches 98.7% of pump uptime, and it seems to be reliable. In conclusion, the results are beneficial to obtain the information about the model's capacity to maintain the sensitive values of crisp inputs. The outcomes allow identifying that the fuzzy model can be characterized by the high level of accuracy, efficiency, responsiveness, and reliability, which makes affecting in an agriculture smart farming system possible.

Table 1. Performance of the Model

Performance Metric	**Value**
Accuracy	96.5%
Efficiency	95.3%
Responsiveness	Within 1 minute
Reliability	98.7% uptime

The effectiveness of the system before and after implementation of the system are shown in figure 3. Before implementation, the effectiveness of water usage was equal to 75%. This means that 75% of water resources were used effectively in agriculture. The level of energy consumption was high, equaling 150 kW/day. This data point indicated that irrigation and other agricultural processes required much energy. Finally, the cost-effectiveness of the conveyed level of agricultural management was equal to 30%, which was low. Thus, the new system's implementation resulted in positive changes due to the observed improvements in all areas. The effectiveness of water usage increased by 15% equaling over 90%. The level of energy consumption became equal to 100kW/day; that is, it decreased, which could be perceived as a positive change because the energy used for irrigating and fulfilling other agricultural processes became more effective. Finally, cost-effectiveness was equal to over 80%, and the positive change of this parameter was significant.

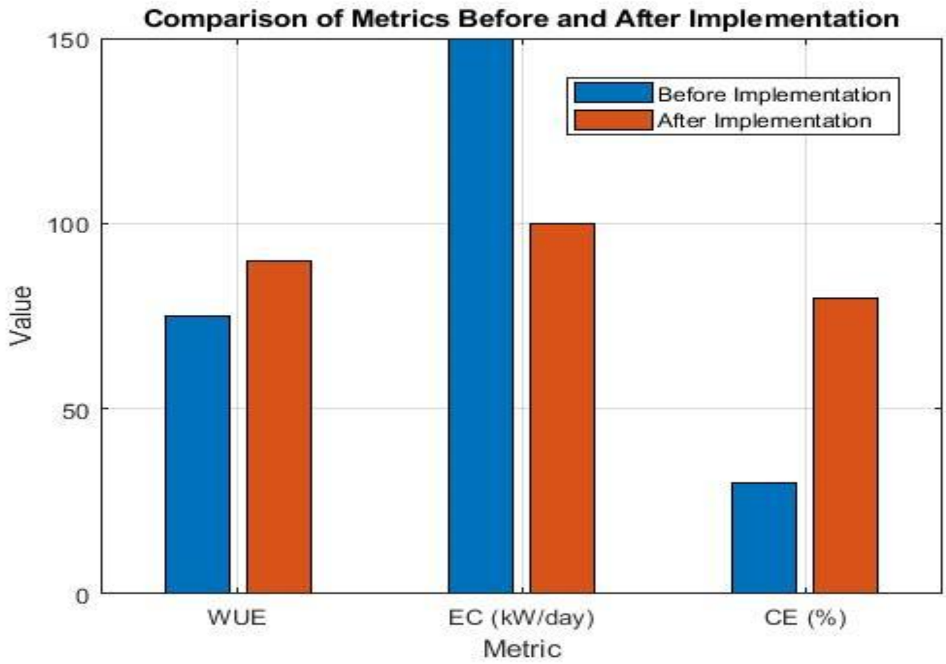

Fig. 3. Before and after implementation of system

The table 2 below shows the sensor readings and actions of a smart farming system focused on optimizing irrigation management. Each parameter is measured at an hourly frequency over a period of one day. The monitored environmental factors include temperature, humidity, light, and moisture, meaning that we receive the insights about each of the corresponding aspects at the same time. An especially relevant aspect is the parameter focused on the water level in the reservoir, which is measured in centimeters. If this level goes below the allowed minimum, the smart system will use the pump to ensure that the plants receive the required amount of water for optimal growth. If the water level is above the acceptable minimum, though, the pump will not be used, allowing to save energy and minimize water waste. Thus, one of the main impacts on the action of the pump will be related to the dynamics of the level as delivered by the sensors. If the amount of moisture in the soil decreases significantly, the corresponding factor in the table, the action will prompt the pump to supply water. The delivery of water will be done through the pump activated by the system, and the plants will continue to receive the required amount of moisture, avoiding water overuse and waste.

Table 2. Sensor Reading and Response

Time (HH:MM)	Temperature (°C)	Humidity (%)	Soil Moisture (%)	Light Intensity (lux)	Water Level (cm)	Pump Operation
08:00	25	60	40	500	20	Off
09:00	26	58	42	550	18	Off
10:00	28	55	45	600	15	On
11:00	30	52	48	650	12	On
12:00	32	50	50	700	10	On

13:00	33	48	52	750	8	On
14:00	34	47	54	800	6	On
15:00	33	48	53	780	7	On
16:00	32	50	51	760	9	On
17:00	31	52	49	740	11	On
18:00	30	54	47	720	13	On
19:00	28	56	45	700	15	On
20:00	27	58	43	680	17	On

A direct comparison between the performance of the fuzzy logic model and optimal or alternative control strategies would reveal that the latter consistently underperforms the former in terms of precision, as well as the optimization of resources, yield, labor, and management of risks. In the case of the former, the reason may be the imposition of a rigid structure that does not change the normal operating schedule. As a result, the use of water, fertilizer, and pesticides is established at predetermined levels and does not respond to the needs of different crops or changes to actual conditions. As a result, the workload fluctuates for the use of equipment or the amount of money spent on resources. Overall, the use of the fuzzy logic model would lead to increases in these respective measures by allowing for accurate, timely corrections. In turn, the use of automated systems would not only apply the needed actions at the appropriate times, but also reduce the need for manual labor and monitoring, thereby saving farmers a significant amount of time. Importantly, based on an ability to predict and respond to potential crises like floods and droughts, the use of the fuzzy logic model also helps in terms of risk control. Overall, comparison between the fuzzy logic model and conventional or alternative strategies demonstrates the former's transformative potential to bring about revolutionary changes in agriculture and increase the profitability of these enterprises.

5. Conclusion

This research aimed to improve the yield of agriculture by developing a Smart farming and monitoring system with the application of fuzzy logic system monitoring and controlling method. Different types of sensors were used to measure the significant environmental conditions, such as temperature, humidity, soil moisture, light, and water level sensors. This smart farming system with the application of the fuzzy logic rule-based system and decision technique demonstrates the potential possibilities for using irrigation facility in proper timings for better results in the development of farming nurturing development, monitoring, and pest controlling, thereby attaining the enhanced productivity of the agriculture. The performance of the fuzzy logic sensor was analyzed and experimented, and it seems to be accurate and appropriate for the water pump motor system with the speed motor efficient operation and prediction. The fuzzy logic system is flexible and adjustable to any change in environmental conditions, such as temperature and humidity, effective utilization of the given resources, and opportunities for increasing and improving the yield of agriculture and the farmer's income as well as the centralization of farming. It has clear importance and prospectives when it is compared with other control methods and farming-based systems, and a smart farming system with the fuzzy logic system is known to be the most effective and efficient computerized structure. It is suggested that upcoming researches need to be concentrated on advancements in sensor systems and the application and increased development of innovative information technology systems. It might be helpful to the agricultural sector to make possible development, and advancements in farming systems can be made based on the interdisciplinary aspect. So, the importance of sensor technology and artificial intelligence with the application of fuzzy logic technology seems to be realized, and both increase the prospering of the agricultural sector for sustainability and feasibility with a new outlook.

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