Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025

Intelligent Irrigation using Abiotic Sensing and Control Theory

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***Abstract*— SMART irrigation systems have a vital function in sustainable agriculture by optimizing water-use efficiency and complying with SDG 6. This article discusses an integrated system consisting of sensory systems and control approaches, such fuzzy logic, for intelligent irrigation. Real-time environmental sensing, soil-water modelling with first-order transfer functions, and MATLAB and Simulink simulation form part of the study. It measures system performance using metrics like steady-state error and water savings. The framework fills the gap that exists between theoretical models and real-world field applications, advancing precision farming using scalable, cost-effective, and environmentally friendly irrigation options.**

***Keywords*— Abiotic Sensing, Fuzzy Logic Control, Feedback loop control, Closed-loop system, Set point regulation**

I. INTRODUCTION

With rising climatic conditions and worldwide water scarcity, sustainable agriculture has become the topmost priority for maintaining food security. Conventional irrigation methods like manual watering and flood irrigation are inefficient due to their wastage of water, labour-intensive nature, and uneven delivery. These drawbacks present serious challenges, especially in areas where agricultural productivity is crucial but water resources are scarce. In order to address these critical challenges, agriculture is moving toward smart irrigation systems that maximize water delivery according to real-time climatic conditions. This paper proposes a new technique that integrates abiotic sensing and control algorithms to improve the accuracy and efficiency of irrigation. By incorporating soil moisture, temperature, and humidity sensors with microcontrollers and actuators, the system provides dynamic control of water flow, enabling the system to respond adaptively to changing environmental conditions. The purpose of this paper, Control-Based Smart Irrigation Using Abiotic Data, is to explore the efficacy of control theory in smart irrigation, illustrate its potential for optimizing water consumption, and identify its wider application in promoting sustainable agriculture.

Recent studies pointed out the ability of automation to enhance water use efficiency and yields by using sensor-based control systems. These systems reduce labour, maximize resources, avoid over-irrigation, and conserve soil. Research by Liu and Xu (2018) and Ganjeer (2019) indicated that automated irrigation can enhance plant growth (more than 15%) and save water (up to 27%) compared to manual irrigation.

Precision farming uses smart technology to help farmers water crops more efficiently by checking and predicting soil conditions. Zhang (in 2020) used wireless sensors to track moisture and nutrients but didn't include prediction. Ramson used LoRa (Long range) technology for soil health but didn't calibrate the sensors. Other system faced problems in villages due to poor Wi-Fi. Dos Santos used LoRa with prediction, and Maroufpoor used advanced math for moisture prediction. This study steps further ahead as it utilizes both Wi-Fi and GSM networks together with precise sensors and a prediction algorithm that can forecast soil moisture up to 10 days ahead of time with 80–90% accuracy [2]. Even with these benefits, challenges in implementation are cost, reliability, and infrastructure requirements, particularly in rural settings. These systems address drought-related agricultural challenges by ensuring timely irrigation, thereby conserving water and improving crop resilience in climate-sensitive regions [1]. Within the frame of crop-specific applications, recent research examines automation's operational efficiency and water saving advantages, particularly in high-value crops like rice. The result highlighted the ways through which automated systems play a crucial role in diminishing labour intensity and irrigation cycles [4]. IoT-based smart irrigation systems are gaining popularity as a smart method of conserving water and enhancing agriculture. Obaideen et al. (2022) demonstrated how sensors, cloud storage, and forecasting tools can be used to monitor weather and soil to irrigate crops more effectively. They help to conserve water, produce healthier crops, and save money. Although the systems being useful, they pose problems such as being expensive, maintenance, and safety of data. This research indicates IoT can make agriculture more effective and sustainable in the future [3].

An extensive literature survey of current literature on automated irrigation systems shows a wide range of research efforts dedicated to agricultural water management. The systematic review highlights the pivotal position of Internet of Things (IoT) technology in promoting water-saving practices in agricultural systems. It supports the potential of IoT in transforming irrigation practices into more adaptive, efficient, for future agriculture. [5]. Prathyusha and Suman (2012) created an automated microcontroller-based drip irrigation system to better utilize water usage in agriculture. In contrast with conventional techniques where water is lost and plants commonly develop diseases, this system only irrigates where and when irrigation is necessary. It conserves 20–80% water and fertilizer and decreases weeds by half, also resulting in healthier crops. This model demonstrates how farmers can use automation to produce more with less, making agriculture more intelligent and sustainable [9]. Smart irrigation systems have also picked up momentum through sensor-based technologies, explore how smart sensors and automation can make watering processes more efficient, alleviating water scarcity issues while enhancing operational efficiency in both small-scale and industrial agricultural sectors [6]. Automated irrigation systems respond to increasing water shortages and the efficiency of irrigation in farming and home gardening. Arduino UNO and soil sensors are widely used in research to develop affordable and automated systems. Simple systems water when moisture drops below 25–30% and cease at 50%. Although cloud-based monitoring improves performance, it increases expenditure. Alternatives such as fuzzy logic have been sought for mass adoption. This work presents a reduced, cost-friendly model based on direct sensor control without internet connection. These systems enable time-based watering, save water, and enhance crop health [7]. Agricultural automation has progressed with AI to address issues such as inefficiencies in irrigation, pest control, and yield prediction. Initial expert systems progressed to more adaptive technologies such as Artificial Neural Networks (ANNs) and Fuzzy Logic for crop management and irrigation forecasting. These innovations are evidencing AI's revolutionary power to transform agriculture and enhance resource use efficiency [8]. Another notable advancement is the incorporation of control theory in irrigation system design highlights the potential of feedback and feed-forward control mechanisms to enhance accuracy of water irrigation [10].

Conventional techniques, such as PID (Proportional-Integral-Derivative) and MPC (Model Predictive Control), suffer from computing burden and slow response rates, thus longer operation time. Rise of fuzzy logic systems in recent times has shown promise to provide a computation less demanding and an alternative with low complexity, whereas maintaining the same performance as MPC. This paper investigates the use of fuzzy-based MPC for optimal, real-time irrigation control [11]. Fuzzy-PID hybrid controllers have been investigated to enhance accuracy and efficiency of smart irrigation systems. A Fuzzy-PID irrigation controller specifically for rice cultivation, using water level information and growth stages of rice to inform irrigation decisions. This is a stronger solution provided by the hybrid control approach with faster response, hence capable of being used in precision irrigation of water-sensitive crops such as rice [12].

This paper comprehensively simulates and analyses an intelligent irrigation system based on fuzzy logic control with MATLAB and Simulink. The simulations include a wide variety of environmental conditions, mostly soil moisture, temperature, and rain, that are grouped into a control system to dynamically manage irrigation in real time. It first constructs a mathematical model of soil water retention as a first-order system with delay with environmental disturbances to mimic real behaviour. Signal generation blocks are used to simulate abiotic variables, which are input into a Mamdani-type Fuzzy Logic Controller. These include important steps like input variable fuzzification through triangular membership functions, rule-based formulation based on expert decision logic, and defuzzification through the centroid method for producing control signals. The response of the pump, being the actuator, is represented to assess performance for various simulation scenarios such as sudden rain showers, sinusoidal temperature fluctuations, and soil moisture content changes. The responsiveness and flexibility of controller are portrayed through real-time plots and scenario-by-scenario tabulated results. It further considers fuzzy inference processes, interpretation of actuator outputs, and system behaviour over dynamics. Such exhaustive simulation protocol lays emphasis on applicability of fuzzy logic-control systems to deploy in environmentally responsive precision agriculture.

II. METHODOLOGY

The technique provides an end-to-end step-by-step approach adopted during the design, modelling, and simulation of a computerized irrigation system responding to abiotic factors of the environmental conditions like temperature, soil wetness, and precipitation. All these steps incorporate the identification of environmental data inputs, design of system architecture, planning for integration of sensors, development of a control algorithm and progressive testing to get desired performance. It ensures the system to be precisely designed according to environmental conditions for effective use of water in agricultural lands.

A. Fuzzy Logic Controller

A Fuzzy Logic Controller (FLC) is a rule-based control technique that has the ability to control nonlinear systems and fuzzy inputs without an exact mathematical model. Unlike conventional controllers, which rely on precise equations, FLCs utilize linguistic variables, fuzzy rules, and inference mechanisms to represent system behaviour. The process begins with the identification of the input and output variables of the system, which are converted to fuzzy sets through fuzzification. A rule base converts these inputs to outputs using if-then rules, and the fuzzy inference engine operates on this data to generate a fuzzy output. Finally, defuzzification converts this output to a control action. FLCs provides significant benefits, including being simple, easy to realize, and offering high performance in varying situations. They are suited for advanced, nonlinear systems and are widely used in industrial automation, power electronics, robotics, household appliances, and medical devices. Their simple logic makes them ideal for flexible and adaptive control applications across different domains.

B. Mathematical Modelling:

The soil's water retention is modelled as a first-order system with time delay:

$$G(s) = \frac{Ke^{-Ls}}{T(s)+1}$$

where K is the system gain, T is the time constant and L represents the delay between irrigation and observed moisture change. This model captures the behaviour of the soil in a closed-loop system. Environmental disturbances like temperature and humidity are added as input variations in the simulation. To manage the delay, Fuzzy Logic Controllers incorporate delay handling through rule-based reasoning, ensuring a stable moisture control. This method enables the controller to predict the system response instead of simply responding to it, improving stability against unforeseen environmental variations.

C. Identification of Input and Output Variables:

The system incorporates three environmental factors as inputs. Soil moisture represents the soil's water content. Temperature affects evaporation rates and plant water requirements. Rainfall acts as a natural irrigation source, reducing artificial water demand. The output variable is Pump flow rate that controls the volume of water delivered to the plants.

D. Fuzzification of Input Variables

The input values for soil moisture, temperature, and rainfall are converted into fuzzy sets using simple triangular-shaped membership functions. Soil moisture is classified as Low at the lowest end of the scale and High across a range from 45 to 75, with the average of 60. Temperature is divided into Low, peaking near 28, and High, with the average of 40. Rainfall is represented as No, for values around 50 and Yes, for values from 50 to 100, with the maximum at 100. These fuzzy sets help the system interpret input data for smooth logic evaluation.

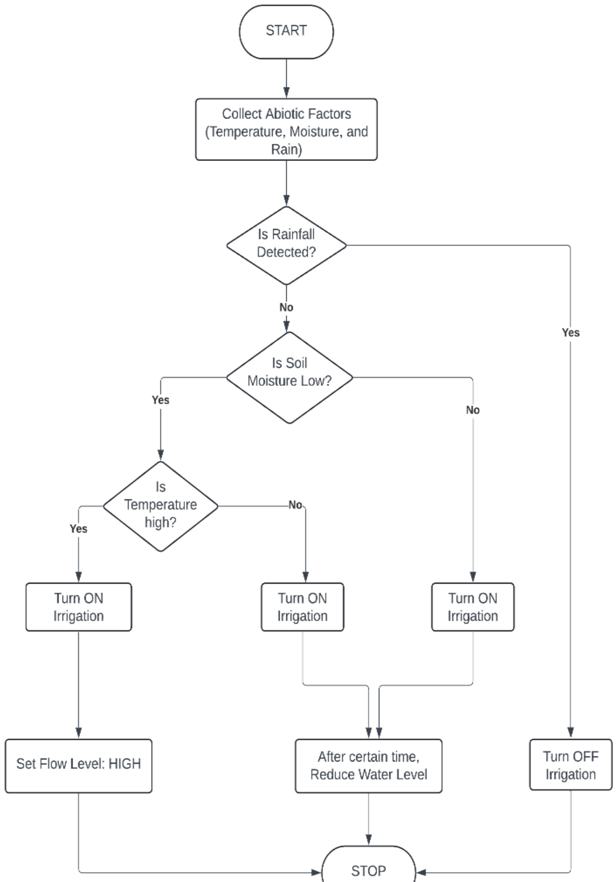

Fig.1 Logic Flow for Irrigation System

E. Rule Formulation in Fuzzy Control

The behaviour of the system is controlled by a group of simple decision-making rules using common language, maximum and minimum logic operations, with OR logic in max function and the AND logic in the min function. The rules for decision-making are as follows: (1) If rainfall or soil moisture is less, then the pump is activated; (2) If soil moisture is high and temperature is low, then the pump is run at a moderate flow rate; (3) If soil moisture is high and temperature is high, then the pump is run at a moderate flow rate; and (4) If soil moisture is high and rainfall is available, then the pump is shut off. These regulations allow the system to make dynamic changes to irrigation levels in response to environmental conditions, optimizing water use. Each rule is evaluated according to fuzzy logic rules, making sure the system performs well even in variable data from sensor, or uncertain environmental conditions.

F. Fuzzy Inference and Defuzzification Process

With a provided set of inputs, the system first determines the degree to which the inputs are elements of predefined fuzzy sets through membership computing. The system, then uses fuzzy logic operators to calculate how strongly each rule applies based on the input conditions. The implication step modifies the output fuzzy sets through the application of the min method according to the rule strengths. Finally, the system applies defuzzification, the centroid method, to convert the fuzzy aggregated output to a crisp control signal, which is then used to efficiently drive the irrigation pump.

III. IMPLEMENTATION

A. Signal Generation and Input Simulation

With sensor readings in real-time, signal generator blocks are used to model soil moisture, ambient temperature, and Step block for rain. Moisture signal generator simulates variation in soil moisture with a constant block or dynamic signals such as sine functions. These signals are scaled within the range 0–100 as specified in Fuzzy Inference System (FIS). Similarly, for Temperature signal generator simulates change in environmental temperature and produces values within the range of 0–50. Both are required to analyse the system response to changing conditions. The Rain step block is used to simulate a rain phenomenon. The block is initially set to represent dry conditions and changes at a predefined simulation time to a value representing rainfall. This setting is crucial in simulating the system ability to cut off irrigation during natural rain. The Mux block is applied to multiplex the outputs from the rain, temperature, and moisture signal generators into a uniform signal. The multiplexed signal serves as input for the fuzzy logic controller. The Mux block combines different environmental inputs into a single signal, making it easier for the FIS to process them. All these input simulation blocks facilitate controlled experimentation over diverse scenarios.

B. Fuzzy Logic Controller Block

The Fuzzy Logic Controller (FLC) within the irrigation system uses a Mamdani-type Fuzzy Inference System (FIS), (which is one of the most common fuzzy logic models that utilises fuzzy sets both for inputs and outputs to emulate human decision-making). The input data such as rainfall, temperature, and soil moisture are initially transformed into fuzzy values through triangular membership functions before being processed. The system then examines these inputs against IF-THEN rules as mentioned previously, employing logical operations such as minimum and maximum method. On analysing the rules, system applies the centroid method to covert the fuzzy output to a control signal that guides the operation of the water pump. The Mamdani method proves effective in coping with uncertainty within data and in making intuitive control decisions. Moreover, Rule viewer provides real-time activity and displays output degrees, optimizing the process of the system to support efficient irrigation.

C. Actuator Control Signal Display

The final output from the fuzzy controller is displayed using Display block, which acts as a virtual actuator. This output value ranges from 0 to 100, shows the control level of the irrigation pump. A lower value indicates no irrigation, while higher values suggest increased water flow. For example, an output of 50 indicates a moderate level of irrigation required under the simulated environmental conditions. This visual feedback confirms the system's operational decisions and helps to validate its effectiveness.

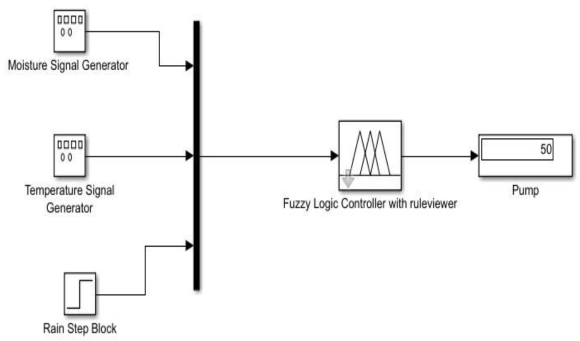

Fig.2 Simulink Model for Automated Irrigation Control

IV. RESULTS AND DISCUSSIONS

In simulation, they demonstrate the effectiveness of the suggested fuzzy logic control system in regulating irrigation based on abiotic factors. The system adapts well to fluctuating environmental parameters, which demonstrates its suitability for maximizing water utilization in agriculture. This study validates model's applicability and provides a platform for further enhancements and real-time use. In general, the approach aids in promoting sustainable agriculture via the promotion of intelligent irrigation control systems with dynamic responses to environmental changes. Additionally, the inherent adaptability of the fuzzy logic method offers a testament to its strength in the management of uncertainties found in natural environmental conditions.

TABLE I. SIMULATED IRRIGATION SCENARIOS AND CORRESPONDING PUMP OUTPUT

Scenario	Soil Moisture (%)	Temperature (°C)	Rainfall (Yes /No)	Pump Output
Scenario 1	25	20	No	10
	20	25	No	15
	15	30	No	25
	10	35	No	35
	30	40	No	20
Scenario 2	40	10	No	15
	35	15	No	18
	30	20	Yes	10
	25	25	Yes	5
	20	30	Yes	8
	15	35	No	25
Scenario 3	30	20	No	20
	25	25	No	22
	20	30	Yes	12
	15	35	Yes	5
	10	40	No	35
	35	35	No	18

A. Simulation Results

To evaluate the efficiency and flexibility of Mamdani-type fuzzy logic irrigation system, three scenarios of different simulation experiments were designed. In each scenario, the most critical factors - soil moisture, temperature, and humidity were altered to challenge the performance of the system under predefined conditions. The objective is to evaluate the system's responsiveness, accuracy, and effectiveness in making decisions to maintain optimal irrigation levels. The findings of each case are discussed below.

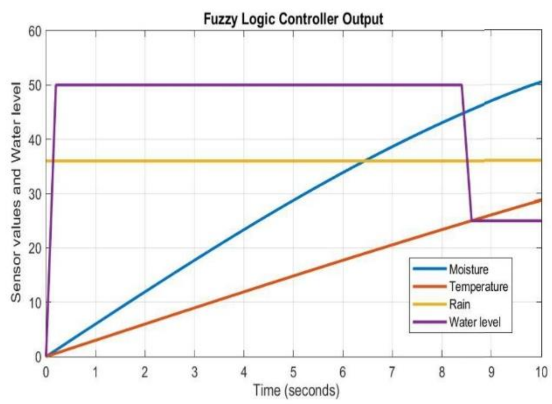

Fig.3 (a) Real-time variation in pump output in response to abiotic factors

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025

In Situation 1, the system's capacity to counteract rising evaporation caused by temperature variations was tested. Humidity was kept constant at 50%, while ambient temperature varied from 20°C to 40°C to mimic temperature fluctuations. The above Fig.3(a) shows that the irrigation system efficiently regulates the water pump output in real time according to changing soil moisture levels while temperature remains constant. When soil moisture goes from dry to wet, the pump output also falls sharply, confirming the effectiveness and precision of the applied control rules in ensuring moisture-sensitive irrigation. This adaptive response proves the system's capability for effective water management under different soil conditions.

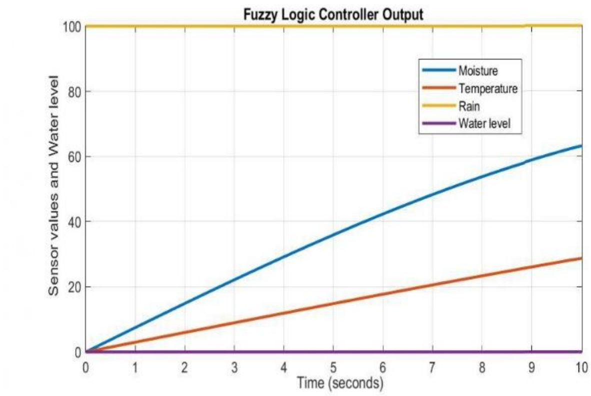

Fig.3 (b) Real-time variation in pump output in response to abiotic factors

To mimic a complicated environmental profile, this Situation 2 includes dynamic 24-hour sinusoidal changes in temperature, humidity, and rainfall. Temperature varies sinusoidal between 10°C and 35°C, also humidity varies sinusoidal between 30% and 90%, and rainfall is simulated with a sudden rise at 12-hour mark. The Fig.3 (b) is the plot that illustrates how a FLC varies the water pump in accordance with moisture, temperature, and rain. Initially, decreased moisture and increased temperature trigger the pump to rise. On rain, the pump output level drops since rain fulfils the requirement. After rain, increasing temperature triggers the pump to bring back moisture. Stable conditions result in a moderate pump setting at the end.

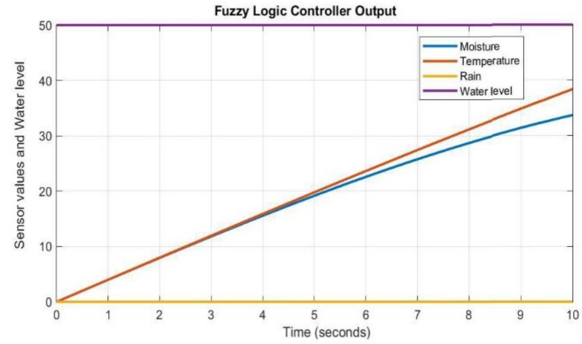

Fig.3 (c) Real-time variation in pump output in response to abiotic factors

The graph from Fig.3 (c) illustrates how FLC varies water pump levels (0-50 units) in response to varying abiotic conditions as Situation 3. The pump goes up slowly at first to compensate for low moisture and increasing temperatures. During rain, the pump goes down as rain covers water requirements. The pump returns to operation after the rain at a controlled rate (reduced rainfall or no rainfall) to replenish water lost by evaporation. The system reveals an inverse correlation between rain and pumping, with elevated temperatures and decreased moisture initiating increased pumping. The intelligent FLC smoothly adjusts to real-time changes, optimizing water use, efficient irrigation, and stable soil conditions, to keep abiotic changes under control. This minimizes water wastage and maintains consistent soil conditions that are critical for plant health.

Critically, rainfall is seen to be the overriding factor in the control strategy, resulting in a direct and significant reduction in pump output, thus saving water efficiently. Such behaviour is repeatedly observed in all simulation tests. In case of detecting rainfall, the system provides topmost priority and either shuts off or significantly diminishes the pump operation, regardless of whether the soil is dry, or the temperature is high. This smart solution shows the system's preference for natural irrigation supplies over man-made watering, toward water conservation. Under Scenario 2 and Scenario 3, adding a rainfall step signal at a mid-point within simulation triggers a significant drop in pump output even during rising temperature, implies the controller's capacity to suspend irrigation in times of rain and restart only when needed. In addition, the fuzzy logic controller demonstrates that it can control the activity of the pump smoothly rather than turning it completely on or off. According to sensor data in real time, it adjusts the flow of water, thus saving energy and maintaining the system operating more steadily. This adaptive management allows the system to achieve constant soil moisture conditions while minimizing mechanical stress on the pump. In summary, the simulation validates the controller's efficiency in decision-making with multi-variables, improving irrigation accuracy, and primarily minimizing water wastage.

B. Discussions

The results prove the fuzzy logic controller to be effective in managing irrigation by adjusting pump output dynamically according to abiotic changes. The system keeps soil moisture at levels favourable for plant growth as proven by the sensitive rise in pump output when soil moisture is low. Fuzzy logic control adjusts pump output gradually instead of turning it on-off like traditional systems. This reduces stress on the pump and helps save energy. Soil water potential is the selected main control cause of the irrigation system. The pump output has a strong opposite relationship with soil moisture, reflecting the system's priority to keep the soil adequately moist. Temperature has an important secondary influence, especially in situations of high evaporative demand. The system makes up for higher water loss under elevated temperatures by boosting pump output, even at moderate levels of soil moisture. Rainfall, when it occurs, overrules the other inputs, making the system withhold irrigation and save water. In comparison to conventional on/off control systems that are based on moisture levels alone, the suggested fuzzy logic method has some benefits. The fuzzy logic system offers a more sophisticated and dynamic response to changing conditions in the environment, leading to smoother operation of the pump and possibly less water usage. The capability to accept multiple input variables, like temperature and rainfall, enables more efficient irrigation decision-making, which results in enhanced water-use efficiency. The advantages of the fuzzy logic-based system are its flexibility, multi-variable input acceptance, and smooth control. The limitations of the simulation, such as its simplified modelling of actual agricultural environments and the requirement for custom fuzzy logic parameters, are noted.

V. CONCLUSION

In this research, a fuzzy logic-based irrigation control system was conceived and simulated to counter the issues of effective water resource management in agriculture. The performance of the system, tested under various environmental conditions, proved its flexibility and stability in handling irrigation dynamically according to changes in soil moisture, temperature, and rainfall. By employing fuzzy logic, the system achieves orders of magnitude in improvement over the traditional threshold-type control methods with smooth pump output modulation that does not wear mechanical parts and has improved energy efficiency. The research proved that the soil moisture was the primary force behind irrigation and that the system showed a clear negative correlation among the moisture levels and pump output. Temperature and precipitation also have important functions, and the system boosts pump output during warm weather to compensate for evapotranspiration while restricting irrigation during rain. Such adaptive traits suggest the potential for fuzzy logic to improve water use efficiency and farm productivity. While the system has its advantages, such as its handling of multi-variable input and ease of control, there are several weaknesses listed by the research, such as idealized models of actual conditions and the need for extra calibration of the fuzzy logic parameters.

Future research should undertake field trials to validate the performance of the system with real agricultural conditions and to calibrate the model for specific crop requirements and local climates. By offering an efficient, smarter, and responsive management system for water resources, this system can make a remarkable contribution towards sustainable agriculture and improved water-use efficiency across different agriculture conditions. Future improvements to this irrigation system can be testing it in actual farm settings to learn more about how it operates under actual weather and soil conditions. The fuzzy logic rules can be optimized for various types of crops and climates to improve it to be more specific and efficient. Incorporating solar power and advanced sensors can improve the system to be more energy-efficient and precise. Mobile real-time alerts for farmers can also be included to keep them updated about the day-to-day weather conditions. In addition, the integration of machine learning could enhance predictions for water use and make the system even more intelligent. In total, these could assist farmers in conserving more water, enhancing crop yield, and making agriculture more environmentally friendly and cost-effective.

VI. ACKNOWLEDGEMENT

We would like to sincerely thank the faculty of the Department of Robotics and Automation Engineering at PSG College of Technology for their unwavering support and valuable guidance throughout the course of this research. We are especially grateful to our mentors and faculties for their insightful suggestions, encouragement, and continuous motivation, which played a crucial role in shaping this work. We also extend our heartfelt appreciation to all those who contributed directly or indirectly to the successful completion of this project.

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