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IoT-Enabled Fuzzy Logic-based Temperature and Humidity Controller with Irrigation Interval Policy in Outdoor Oyster Mushroom Growing Unit

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Abstract

Small-scale farmers and cultivators struggle to maintain optimal growth conditions and reliably produce high yields, as outdoor mushroom farming is highly sensitive to environmental fluctuations. This paper presents an Internet of Things (IoT)-enabled fuzzy logic-based temperature and humidity control system along with an irrigation interval strategy for an outdoor oyster mushroom growing unit. The proposed system employs temperature and humidity sensors for real-time environmental monitoring and a Mamdani-type Fuzzy Inference System (FIS) to dynamically manage a water pump and cooling fan. To address the excessive water consumption observed in conventional FIS-based control, an irrigation interval-based optimization technique is presented. The findings show that even in the face of changing environmental circumstances, the controller successfully keeps the temperature between 24 and 27 °C and the relative humidity over 70%. Stable performance with a low standard deviation and little tracking error from setpoints is demonstrated by statistical analysis. Additionally, while preserving the intended microclimatic conditions, the suggested strategy is affordable, scalable, and greatly increases resource efficiency by reducing water use by almost 80% as compared to the baseline FIS system.

Keywords: *Precision agriculture, Internet of Things, smart mushroom cultivation, sustainable agriculture.*

1 Introduction

The use of cutting-edge digital technology, especially the IoT, which permits smooth communication between smart devices like sensors, actuators, and embedded systems, is drastically changing agriculture. IoT gathers and analyzes crop-related and environmental characteristics to

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enable real-time monitoring and data-driven decision-making. Food production must rise significantly as the world's population is predicted to reach 9.6 billion people by 2050, and IoT-enabled agriculture is likely to be essential to raising productivity and resource efficiency [1, 2].

Despite these advancements, there are challenges associated with the absence of technical knowledge, costly infrastructural requirements, and dependence on manual labor, which have posed obstacles to the adoption of modern farming techniques by smallholder farmers and rural residents, especially women. Affordable, automated, and easy-to-use cultivation technologies that work outdoors and provide a steady harvest are increasingly essential. Rather than concentrating on costly greenhouses, such technologies should be localized and affordable in this case [3].

The cultivation of mushrooms, especially oyster mushrooms, presents itself as an excellent business venture for self-employment and earning money for farmers at the margin and women. The reason for this is that the growth of such mushrooms requires very little space and they are relatively cheap and very nutritious. Given the current increase in the demand for mushrooms in the country as a result of their nutritive and medicinal value, there has been a significant rise in the production of mushrooms in India from 17.1 metric tons during 2013-14 to 243 metric tons during 2020-21 [4]. However, because mushroom growing is so sensitive to environmental variables like temperature, humidity, and gas concentration, it is difficult to produce consistent harvests outside [5].

Traditional agricultural systems depend largely on manual inspection and regulation, resulting in environmental changes affecting the quality of the product and decreasing its output. It is difficult to maintain the ideal conditions of maintaining the environment, especially temperature lower than 27 °C and relative humidity more than 70% while the crop is growing [6]. There is a pressing need for developing a technology for automatic regulation of the environment which does not require human intervention. This would make the cultivation process easier even for a novice.

Motivated by the aforementioned challenges, this research presents an automated outdoor mushroom farming system using the IoT together with FIS. This system will enable the intelligent control of environmental parameters by using real-time data and control methods that adapt to various circumstances. FIS is influenced by human thinking and provides for the effective management of uncertainties and variations in the environment. As such, this method may be helpful in agriculture through decentralization [7]. Automating processes, such as temperature and moisture levels control, is expected to improve yield reliability, enhance efficiency, and greatly increase profitability for farmers and women at households.

The main achievements of the research may be highlighted as follows:

- An affordable IoT-based prototype for controlling the environment during the cultivation of oyster mushrooms outdoors through ESP32 and sensors.
- The design and deployment of a Mamdani fuzzy inference system with actuators like coolers and pumps for efficient temperature and humidity control.
- The installation of an improved irrigation control system that reduces water waste by using time-based evaporative cooling regulation. Real-world outdoor experimental validation showing consistent environmental maintenance (temperature below 27 °C and humidity over 70%).
- Water consumption can be reduced by up to 80% when compared to traditional management methods.
- The provision of an accessible, scalable, and user-friendly solution to promote sustainable agriculture and enhance rural women's and small-scale farmer’s ability to generate income.

The rest of this manuscript is structured as follows: Related research on automated climate control systems in agriculture is reviewed in Section II. The system design, which includes the IoT architecture, evaporative cooling mechanism, and FIS-based irrigation interval control approach, is presented in Section III. The experimental findings and performance assessment are covered in Section IV. In Section V, the study is concluded and future research directions are outlined.

2 Related Work

Numerous intelligent control strategies have been developed by recent developments in greenhouse management systems and smart agriculture with the goals of enhancing crop output, preserving resources, and optimising environmental conditions. Several studies have suggested sensor-based, AI-enabled, and IoT-driven methods to automate and track important agricultural metrics, especially in greenhouse settings as mentioned in Table 1. To improve the microclimate conditions in strawberry greenhouses, a Low-Cost Active and Sustainable Autonomous Solar Heating System [8] was created and utilising solar thermal technology. The technology showed a 30% decrease in irrigation water consumption and an increase in yield. Its effectiveness is limited by the amount of solar power available, though, and its deployment may need changes to the infrastructure. An Automatic Irrigation and Fertilisation System [9] was designed to deal with irrigation and nutrient optimisation. This IoT-based device automates nutrient distribution and watering by utilising a variety of environmental sensors. Although it successfully lowers the amount of water and fertiliser used, its limitations include sensor calibration, the dependability of the local network, and its inability to integrate with weather predictions.

A Deep Neural Network-Based Control System [10] employed Elman and multilayer perceptron neural networks in cascade to simulate and regulate greenhouse temperatures. These systems require significant computational resources and large training datasets, despite their exceptional accuracy. Similarly, NARX and NARMA-L2 neural controllers [11] have improved setpoint tracking and disturbance rejection by addressing non-linearity in greenhouse systems. Nevertheless, these models often perform poorly in dynamic, unforeseen settings and need a lot of training data. IoT-Based Fuzzy Proportional Integral Derivative Controller [12] has been used for fig farming with an intention to improve environmental management through the use of less complicated logical systems. Sensor-based system performed better than traditional methods in one of its applications on vegetable greenhouse automated irrigation system [13]. The performance of the system may be impacted by its size and other external factors.

Adaptive Microclimate Systems based on WSNs [14] have been devised to detect greenhouse climates spread across various geographic locations. The technology ensures effective maintenance of suitable microclimates using fuzzy-PID control and Zigbee networks, although problems exist with sensor drift and reliability in communication. The climate control system integrated with an intelligent control system, involving wireless components and programmable controllers for large greenhouses, is more commercially oriented [15]. Technology increases crop yields and efficient use of resources, but other expenses are incurred. The Fuzzy Logic Based Intelligent Irrigation Control System [16] is designed such that the amount of water flowing is dynamically altered based on external inputs to increase the efficiency of irrigation. In spite of all its advantages, the effectiveness of the technology depends on accurate data from the sensors used as well as manual adjustments in membership functions depending on the type of crop and soil being used. The Portable Automatic Sensing System [17] was developed to analyze the quality of water used for irrigation by using portable sensors.

Overall, the discussed literature provides evidence of notable advancements in developing intelligent agricultural systems utilizing IoT, wireless sensors and innovative control methods. Some of these technologies have resulted in effective environmental monitoring, resource management and increased productivity of crops. Nonetheless, several deficiencies were identified. First, most of the discussed systems are created for a controlled environment such as greenhouse and depend either on sophisticated computational models, training data, expensive infrastructure or regular calibration procedures. Second, the studies have not paid attention to outdoor mushroom cultivation when environmental conditions change dramatically and are hard to manage. In addition, previous research has been focused on single problems of mushroom cultivation such as irrigation, temperature or climate monitoring instead of presenting a comprehensive system for controlling various cultivation parameters. Thus, there is a need to develop an inexpensive, intelligent and flexible system for controlling various environmental parameters in outdoor mushroom cultivation process. Artificial Intelligence, real-time data processing, and environmental modelling [18] are still necessary in regulated agriculture settings to boost sustainability and production. The goal of the current paper is to propose such a system using IoT technology and integrating FIS into temperature, humidity and irrigation interval control process.

Table 1: Literature review on Automatic Climate Control system for greenhouses

Model Name	Purpose ADM	Limitations VIM
Low-Cost Active and Sustainable Autonomous Solar Heating System for Greenhouses [8]	To enhance microclimate conditions in greenhouses using solar energy for improved strawberry yield and reduced resource use.	Effectiveness may vary with seasonal solar availability and initial setup may require infrastructure adaptation.
Automatic Irrigation and Fertilization System for Smart Greenhouse Farming [9]	To automate irrigation and nutrient delivery using IoT and sensor data for optimized crop growth and resource conservation.	Limited by sensor calibration accuracy, local infrastructure, and lack of integration with predictive weather data.
Deep Neural Network-Based Greenhouse Modelling and Control System [10]	To accurately model and control greenhouse climate using a cascade of deep Elman and multilayer perceptron neural networks.	High computational complexity and reliance on large, high-quality datasets for effective training and generalization.
Neural Network-Based Greenhouse Control System using NARX and NARMA-L2 Controllers [11]	To model and control non-linear greenhouse environments for optimal crop growth using neural predictive and adaptive control strategies.	Requires extensive training data and computational resources, with potential performance degradation under unseen dynamic conditions.
IoT-Based Fuzzy Proportional Integral Derivative (FPID) Control System for Figs Greenhouse [12]	To maintain optimal air and soil conditions for fig cultivation by integrating FPID with IoT for real-time monitoring and automated control.	System effectiveness depends on accurate fuzzy rule design and may need adaptation for different crop types or greenhouse setups.
Automated Sensor-Based Irrigation System	To improve irrigation efficiency, reduce	Performance is influenced by external weather conditions

for Vegetable Greenhouses [13]	labour, and enhance crop yield by comparing automated watering with traditional methods.	and limited scalability due to fixed sensor placement and greenhouse size.
Wireless Sensor Network-Based Adaptive Microclimate Control System for Greenhouses [14]	To monitor and maintain optimal greenhouse microclimate conditions using a fuzzy-PID controller and spatially distributed sensors.	System accuracy depends on sensor calibration and Zigbee communication reliability, which may be affected by environmental interference.
Climate Control Module (CMS) with Intelligent Control System (ICS) for Commercial Greenhouse [15]	To optimize crop yield and reduce energy and water consumption through automated, sensor-driven environmental control.	Higher initial setup cost and dependence on reliable connectivity for real-time data transmission and control.
Fuzzy Logic-Based Intelligent Irrigation Control System [16]	To automate irrigation by adjusting pump speed based on real-time soil moisture and environmental factors using fuzzy logic for efficient water use.	Requires manual tuning of fuzzy membership functions for different crop and soil types, and system performance depends on sensor accuracy.
Portable Automatic Sensing System (PASS) for Precision Farming [17]	To monitor and control irrigation water quality in greenhouses and precision farms through portable sensing of pH, electroconductivity, and water flow with real-time mobile access.	Limited sensor range and dependency on consistent operator handling may affect accuracy and scalability in large-scale operations.

3 Methodology

For automatic outdoor oyster mushroom growing, an intelligent IoT-based control system was developed to continuously monitor and control vital environmental factors including temperature and relative humidity. To maintain ideal growing conditions with the least amount of human involvement, the system combines real-time sensing, actuator control, and decision-making via a FIS.

The suggested method allows for adaptive control of a cooling fan and water pump by combining interval-based irrigation scheduling with rule-based fuzzy logic. The ICAR-Indian Institute of Horticultural Research (IIHR) Mushroom Laboratory in Hessaraghatta, Bengaluru, designed, implemented, and tested the prototype in conjunction with an Evaporative Cooling System (ECS).

3.1 FIS

The control method relies on the application of the Mamdani type of FIS, which suits the conditions of a dynamic environment due to its applicability in nonlinear situations [19]. Compared to Takagi-

Sugeno-Kang, Mamdani fuzzy inference offers more robust performance and provides linguistic results. The functioning of the FIS is threefold and involves three phases, namely fuzzification, rule evaluation, and defuzzification, shown in Fig. 1.

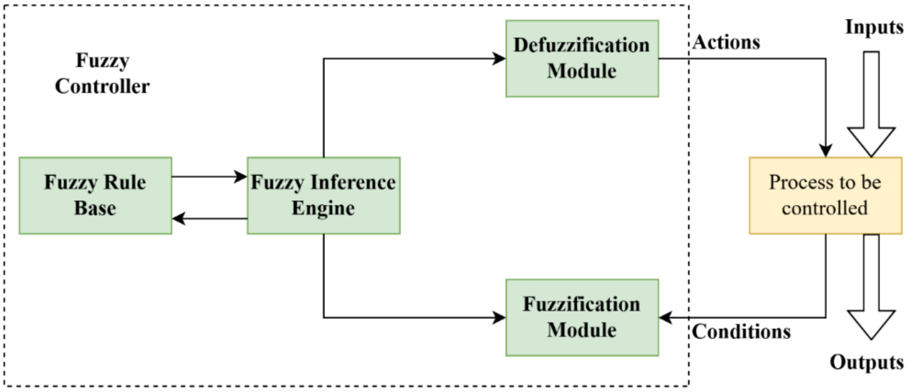

Fig. 1 FIS block diagram

3.1.1 Fuzzification

Trapezoid membership functions (MFs) are employed for inputs such as temperature and relative humidity, while triangular membership functions are employed for output variables such as water pump time and fan operating time. Temperature categories of cold, suitable, and hot and their corresponding ranges are stated in Fig. 2, and humidity categories of dry, suitable, and wet and their corresponding ranges are defined through these MFs.

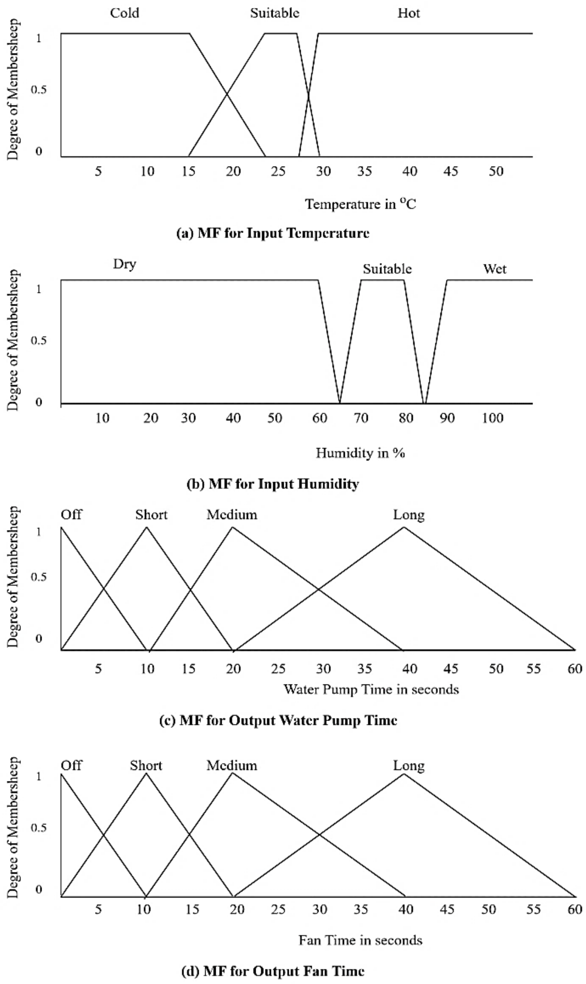

Fig. 2 Membership functions of input and output variables

3.1.2 Rule Base Design

Table 2 summarizes the nine fuzzy rules that were developed to control system behavior. These regulations use environmental factors to decide how long the water pump and cooling fan will run. To guarantee consistent environmental management, the rule basis was created using expert knowledge and iteratively improved using experimental observations [20].

Table 2: Fuzzy rule base

Rule	Input Variable				Output Variable (Time in sexonds)	
	Temperature		Humidity		Water pump time	Fan time
1	Cold	AND	Dry	THEN	Short (0-20)	Short (0-20)
2	Suitable	AND	Dry	THEN	Medium (10-40)	Medium (10-40)
3	Hot	AND	Dry	THEN	Long (20-60)	Long (20-60)
4	Cold	AND	Suitable	THEN	Off (0)	Off (0)
5	Suitable	AND	Suitable	THEN	Off (0)	Off (0)
6	Hot	AND	Suitable	THEN	Off (0)	Medium (10-40)
7	Cold	AND	Wet	THEN	Off (0)	Off (0)
8	Suitable	AND	Wet	THEN	Off (0)	Off (0)
9	Hot	AND	Wet	THEN	Short (0-20)	Short (0-20)

3.1.3 Defuzzification

The centroid (center of gravity) approach is used to transform the aggregated fuzzy outputs into clear control signals, allowing for accurate cooling fan and water pump actuation [21].

3.2 IoT Based Prototype Architecture

The proposed system consists of two primary components, IoT node and Applied Environment System.

3.2.1 IoT Node

The IoT node forms the sensing and control unit and includes

- ESP32 microcontroller for data processing and connectivity
- Two DHT22 sensors for temperature and humidity measurement
- Optocoupler-based relay modules for safe actuation

The node is mounted on the roof of the cultivation unit to ensure accurate environmental sensing and efficient communication.

3.2.2 Applied Environment System (AES)

The AES comprises the physical components responsible for environmental regulation, including

- Cooling fan for temperature control
- Water pump for humidification
- Perforated distribution pipes (0.2 mm diameter) for uniform water spraying
- Connectors (elbow and T-joints) for efficient water flow distribution

The integration of IoT node and AES enables automated sensing–decision–actuation cycles, as illustrated in Fig. 3 and Fig. 4.

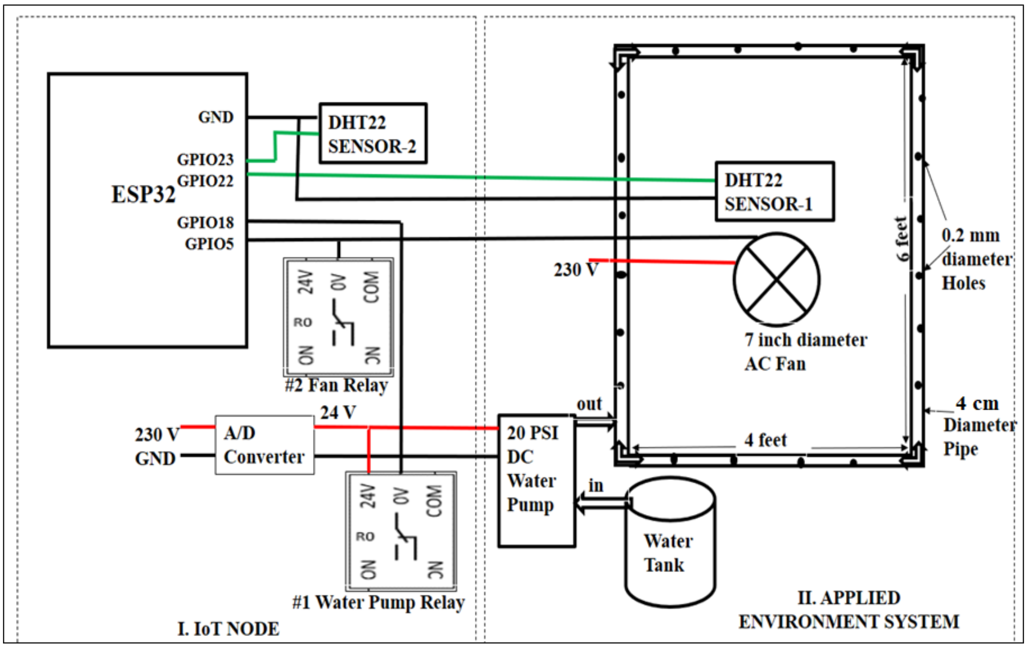

Fig. 3 Schematic block diagram of IoT prototype

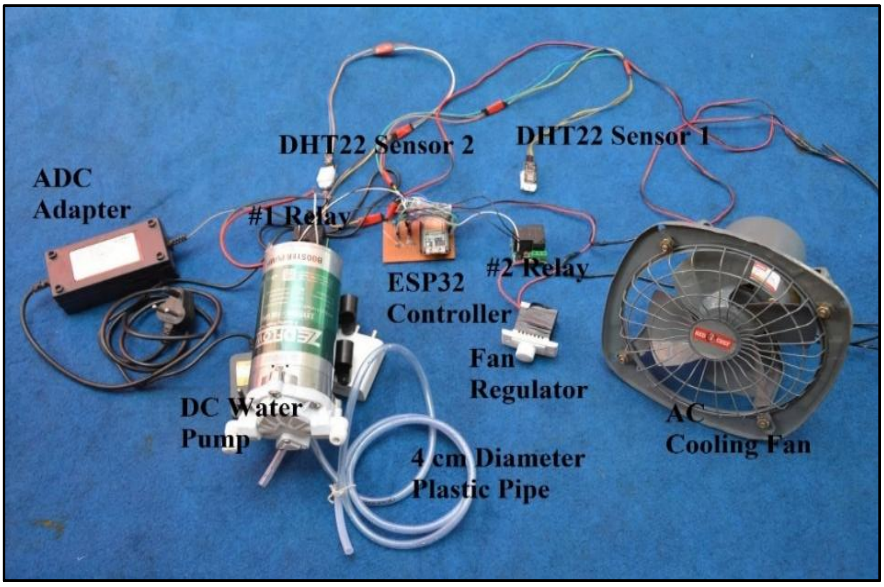

Fig. 4 IoT prototype hardware

3.3 An Evaporative Cooling System

The basic idea of ECS is to cool the surrounding air to a comfortable temperature by drawing heat from the warmer outdoor air by passing it through a wetted patch and allowing the water to evaporate [22, 23]. Consequently, it uses water evaporation to remove heat from a wet surface. Its effect causes the temperature inside the confined space to drop and the relative humidity to rise. The experimental mushroom growing unit (6 × 4 × 6 ft) was built with a vertical rope-based shelving system that could hold up to 100 mushroom sacks, a ventilated plastic ceiling for air circulation, and double-layered gunny sheets on both sides for moisture retention shown in Fig. 5. The gunny sheets, which serve as the evaporative medium, are periodically moistened with water. This design guarantees a controlled microclimate that is appropriate for the outdoor development of oyster mushrooms [24].

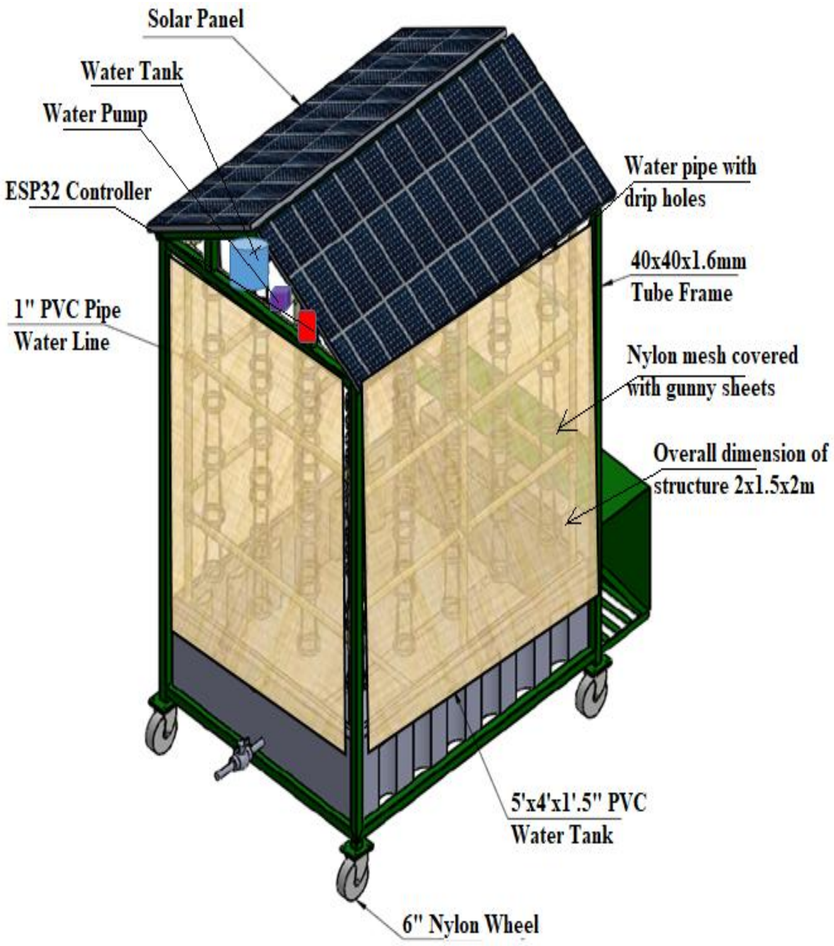

Fig. 5 An Outdoor oyster mushroom growing unit

3.4 Experimental Setup and Deployment

As oyster mushrooms absorb moisture from their surroundings, maintaining a high ambient humidity is crucial in oyster mushroom production rather than directly watering bags [25]. Therefore, it is essential to maintain humidity levels in the growing chamber above 70%. The surrounding gunny sheets in the intended unit were moistened with water.

The ESP32 controller was used to build the FIS algorithm using Arduino C. After preliminary testing, the system was set up in an outdoor mushroom cultivation unit with 70 mushroom bags, each holding 50 g of spawn and 1 kg of substrate (Fig. 6). Water was supplied to the system via a pump mechanism from a 20-liter water tank installed on the roof (refer Fig. 7). Temperature, relative humidity, pump and fan operating times, and other real-time data were continuously sent to the cloud for monitoring and analysis during the system's daily operation from 9:30 AM to 5:00 PM.

The system has proven its effectiveness in maintaining the interior ambiance within the required range during the period from January 5 to January 16, 2023. This period was chosen as the period for testing the prototype, calibrating sensors and tuning the control system. None of the information collected during the commissioning phase was included in the performance evaluation process. The experiment started on January 17, 2023. It can be noted that the temperature was maintained in the range of 24 - 27 °C while the relative humidity level was set to the range of 70 - 80 %. It can be seen from Table 3 that the system was using an excessive amount of water due to the constant operation of the water pump despite the fact that evaporative medium (gunny sheets) was fully saturated with water.

Fig. 6 An experimental setup: an outdoor oyster mushroom growing unit

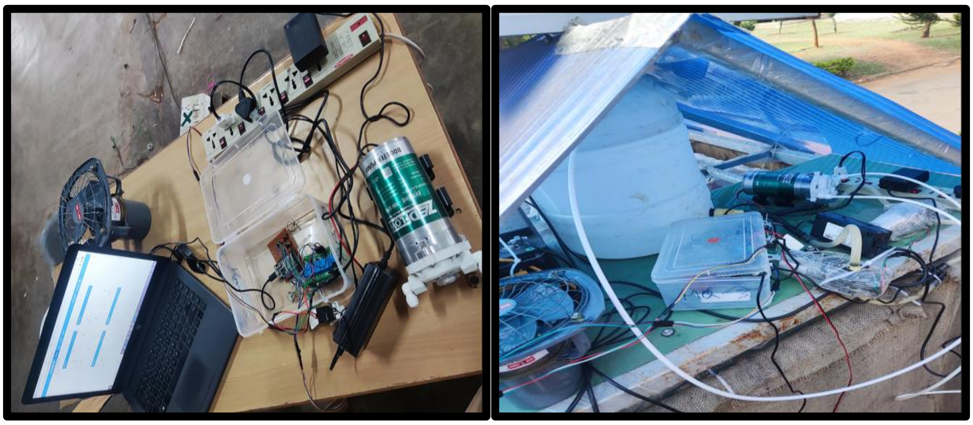

Fig. 7 IoT prototype testing and deployment

Table 3: Day wise experimental setup details for FIS system

Specifications Day Wise	17/01/23	18/01/23	19/01/23	20/01/23	21/01/23
No of bags	70	70	70	70	70
Start Time	9.30am	9.30am	9.30am	9.30am	9.30am
End Time	5.00pm	5.00pm	5.00pm	5.00pm	5.00pm
Average Temperature	27.36℃	24.07℃	20.51℃	20.14℃	22.36℃
Average Ambient Temperature	28.70℃	22.49℃	19.10℃	19.07℃	20.31℃
Average Humidity	68.4%	69.2%	68.5%	68.2%	69.6%
Average Ambient Humidity	26.4%	61.8%	33.6%	52.6%	31.6%
Water Used in liters	220	100	200	140	200
No of bags	70	70	70	70	70

*Start time and end time are as per Indian time offset of UTC +5:30.

3.5 Irrigation Interval-based Optimization Strategy

The plot in Fig. 8 shows that average water used per day depends upon the difference between inside humidity of an outdoor mushroom growing unit and its ambient humidity. When the difference was less, less water was consumed. However, when the difference was more, more water was consumed by system to maintain inside humidity to above 70%, because water required for humidification was more. Furthermore, when the water pump was turned on, the gunny sheets were taking around 20 minutes to be completely saturated for the first time. Once it was saturated, water was drained from bottom end of the gunny sheets. As a result, the water continued to drip on the gunny sheets unnecessarily until the humidity rises beyond 70%. To reduce wastage of water due to gunny sheets water saturation, an irrigation interval-based algorithm was proposed and applied in combination with FIS algorithm integrated in an automatic IoT-based controller to optimize temperature, humidity of an outdoor oyster mushroom growing unit.

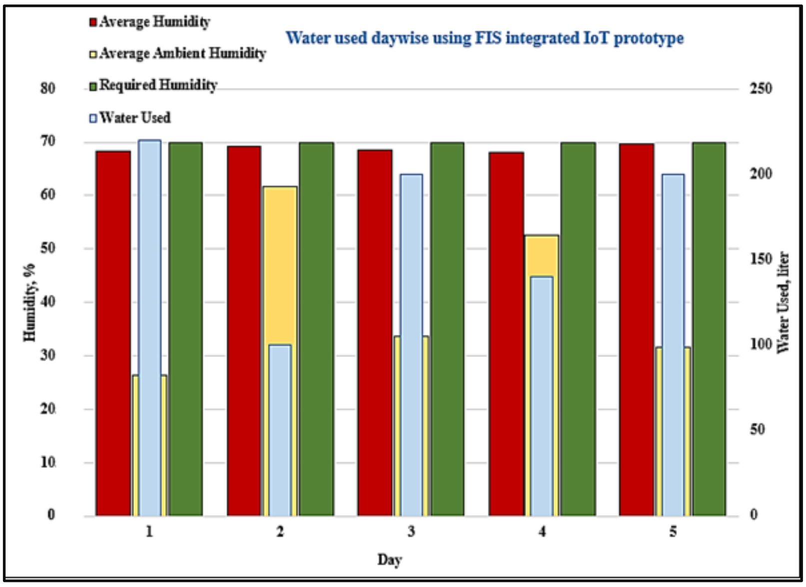

Fig. 8. Water used per day using FIS integrated IoT prototype

A FIS-based irrigation interval algorithm controls the operation of the water pump depending on the internal humidity conditions and the duration necessary to saturate the gunny sheets [26]. The irrigation interval strategies were determined empirically from the experiments carried out from January 5 to January 21, 2023, during the prototype's calibration stage. Fig. 8 shows the correlation between internal humidity, the water used as calculated by the FIS model, and the wetting demands of the gunny sheets. According to the experimental operation characteristics, three internal humidity zones with different irrigation needs were found.

- Internal Humidity is in range of 60%–69%: FIS-calculated pump time was 6.21–20.1 seconds. The pump operated for 20 minutes and remained off for 30 minutes, given the small deviation from target humidity.
- Internal Humidity is in range of 40%–59%: FIS-calculated pump time was 20–30.1 seconds. The pump operated for 15 minutes and turned off for 15 minutes, due to moderate deviation from target humidity.
- Internal Humidity is in range of <39%: FIS-calculated pump time was 30–40.1 seconds. The pump ran for 20 minutes and remained off for 10 minutes, reflecting a large deviation from target humidity.

The Algorithm 1 was coded using Arduino C language and tested on the ESP32 microcontroller of the proposed IoT prototype. After successful implementation and testing phases of the prototype, the Irrigation Interval-based FIS ran continuously from January 23 to January 31, 2023, between 9:30 AM and 5:00 PM every day. Key operational parameters, such as pump operating time, fan operating time, ambient temperature, ambient humidity, internal temperature, and internal humidity, were measured every minute during the experiment and recorded in the cloud.

To exemplify the performance of the system under various environmental conditions, Table 4 shows the values of five days out of the nine experimental days. The days were selected randomly based on ambient temperature and humidity values rather than irrigation performance or water consumption. The results of experiments prove that the proposed Irrigation Interval-based FIS successfully maintained the necessary temperature and humidity in the mushroom growing unit while dynamically changing the irrigation interval depending on internal humidity value.

Algorithm 1: Irrigation Interval based FIS algorithm

```
Initialize humidity, temperature, water pump time (W_t)
Read ambient humidity, ambient temperature
While () do
  | Read humidity, temperature
  | If (humidity< 70%)
  |   | Compute W_t using FIS with input humidity, temperature
  |   |          | If (6.21 <W_t< 20.1) then
  |   |          |     Switch ON water pump
  |   |          |     delay(10)
  |   |          |     Switch OFF water pump
  |   |          |     delay(30)
  |   |          | If (20 <W_t< 30.1) then
  |   |          |     Switch ON water pump
  |   |          |     delay(15)
  |   |          |     Switch OFF water pump
  |   |          |     delay(15)
  |   |          | If (30 <W_t< 40.1) then
  |   |          |     Switch ON water pump
  |   |          |     delay(20)
  |   |          |     Switch OFF water pump
  |   |          |     delay(10)
  |   | End      | End
  | End
End
```

Table 4: Day wise experimental setup details for Irrigation Interval based-FIS

Specifications Day Wise	27/01/23	28/01/23	29/01/23	30/01/23	31/01/23
No of bags	70	70	70	70	70
Start Time	9.30am	9.30am	9.30am	9.30am	9.30am
End Time	5.00pm	5.00pm	5.00pm	5.00pm	5.00pm
Average Temperature (℃)	27.45	27.92	25.19	27.86	27.85
Average ambient Temperature (℃)	32.23	30.77	27.01	29.04	29
Average Humidity in %	72.53	69.60	78.63	78.75	78.43
Average Ambient Humidity in %	23.6	22.22	24.87	27	28.3
Water Used in liters	40	40	30	30	30

*Start time and end time are as per Indian time offset of UTC +5:30.

4 Result and Discussion

Over the course of seventeen days, the developed IoT-based prototype was deployed in an outdoor oyster mushroom growing unit to conduct the experimental investigations. The purpose of the tests was to assess the usefulness and effectiveness of the suggested FIS-based intelligent control system for controlling humidity and temperature in the growing environment. Using the FIS rule base, the IoT system calculated the operating duration for the cooling fan and water pump while continuously gathering data from the DHT22 sensor. For the convenience of the user, all sensor data and system reactions were saved in the cloud and displayed in real time via a web-based interface.

Despite considerable changes in the surrounding environment, the system successfully kept the inside temperature within the intended range. As seen in Fig. 9, the interior temperature was continuously maintained below the crucial threshold of 27 °C even as the outside temperature rose to 37.2 °C. Statistical analysis was performed to objectively assess performance over the full 17-day period; the results are displayed in Table 5. Stable thermal regulation was demonstrated by the mean interior temperature of 25.8 °C with a standard deviation of ±1.2 °C. With regard to the setpoint (27 °C), the mean absolute error (MAE) was 1.2 °C, indicating good tracking performance. The cooling fan ran sporadically, mostly during times when the outside temperature was at its highest, demonstrating the control system's energy-efficient operation.

Table 5: Statistical analysis of Temperature control performance (17-days evaluation)

Parameter	Value in ^oC
Setpoint Temperature	27
Mean Interval Temperature	25.8
Standard Deviation	±1.2
Mean Absolute Error	1.2
Maximum Ambient Temperature	37.2
Temperature Range to be maintained	24-27

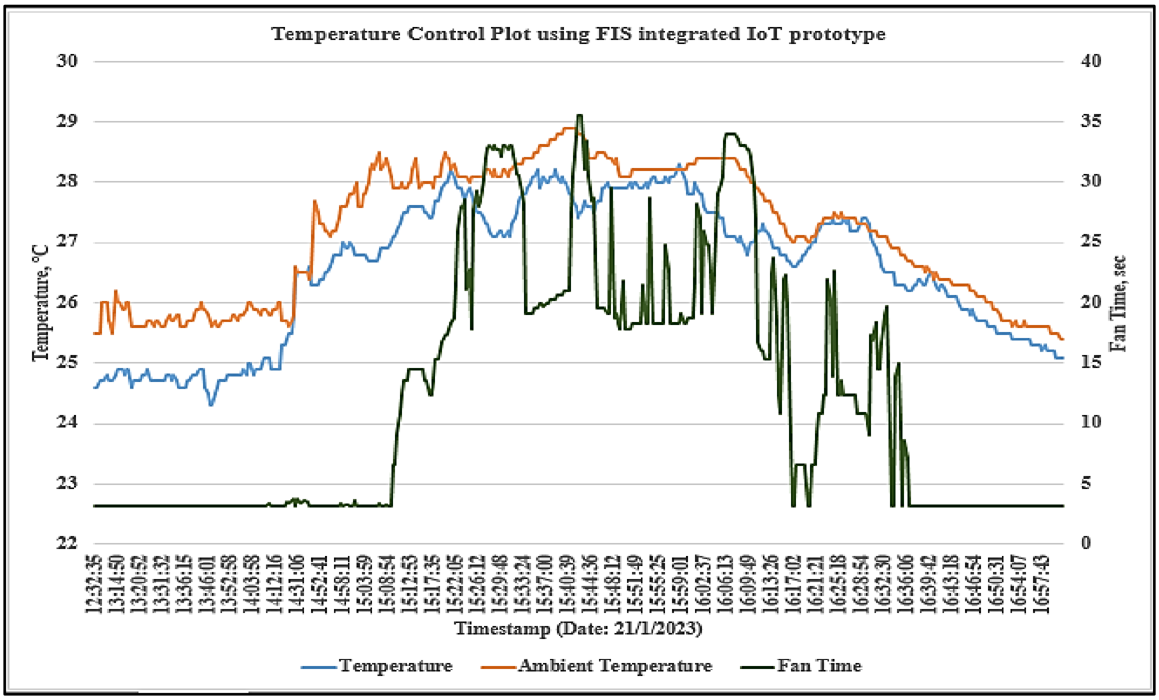

Fig. 9 Temperature control plot using FIS integrated IoT prototype for a day

The device operated excellently within the required relative humidity level beyond 70% to ensure proper cultivation of mushrooms. The controller managed to maintain an ideal relative humidity despite the external environment humidity being below 30%, as indicated in Fig. 10. According to statistical analysis, the average relative humidity during the experiment was 72.6% with a standard deviation of ±3.8% (see Table 6), implying consistent humidity management. Effective tracking across different environments was proven by the average absolute error from the target value (70%) being 2.6%. Nonetheless, the system required continuous pump operation when ambient humidity fell below 40%, leading to excessive water consumption. This shows the flexibility of the FIS controller; however, it also highlights poor water utilization in difficult environmental conditions.

Table 6: Statistical analysis of Humidity control performance (17-days evaluation)

Parameter	Value in %
Setpoint Humidity	70
Mean Interval Humidity	72.6
Standard Deviation	±3.8
Mean Absolute Error	2.6
Minimum Ambient Humidity	<30
Humidity Range to be maintained	70-80

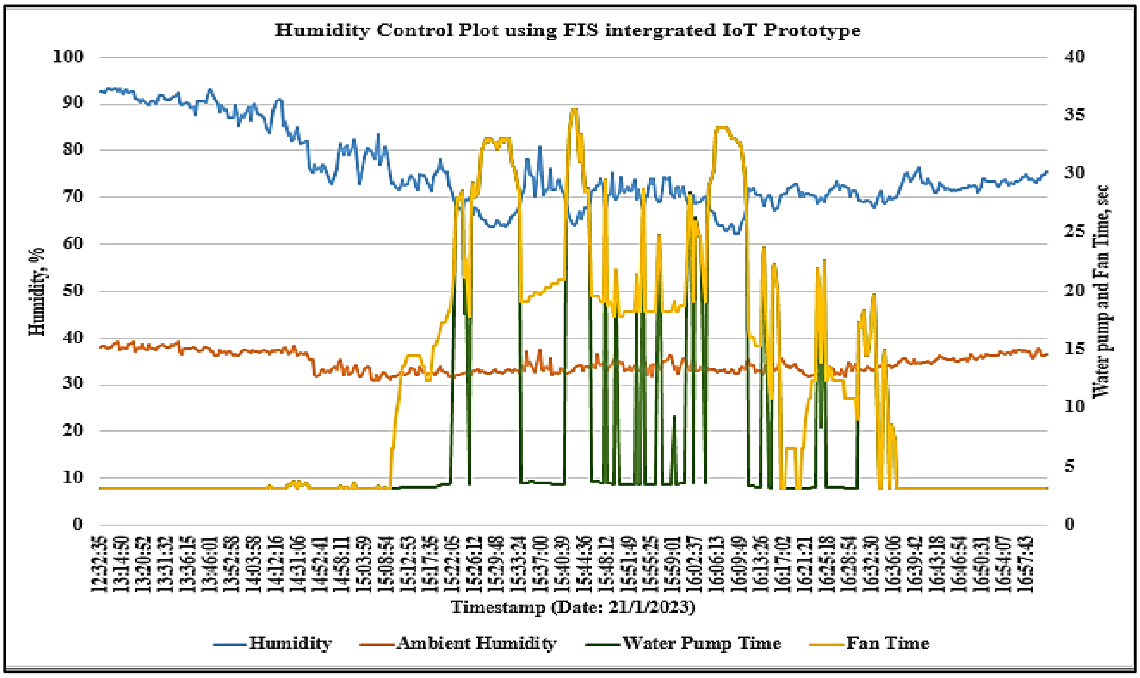

Fig. 10 Humidity control plot using FIS integrated IoT prototype for a day

The water usage in average for the 17 days of testing using the FIS-based system was about 172 liters per day, with variation observed depending on the degree of humidity in the environment. The standard deviation of the water usage was around ±45 liters, showing dependence on environmental factors (see Table 7).

A clear positive correlation was observed between water consumption rate and the humidity differential in which more water had to be consumed in order to achieve the desired level of humidity due to greater variations. Moreover, saturation of the gunny sheets took about 20 minutes for the first irrigation session. Significant water waste resulted from the extra water draining after saturation without adding to the cooling or humidification process.

Table 7: Water consumption analysis of FIS based system (17-days evaluation)

Parameter	Value in L
Average daily water consumption	172
Standard Deviation	±45
Maximum water consumption	220
Minimum water consumption	100

An FIS algorithm based on irrigation intervals was developed and incorporated into the IoT controller to solve this inefficiency. By adding a delay period between consecutive pump activations, the new control technique allowed the system to reevaluate humidity after a certain amount of time before starting irrigation again. As shown in Fig. 11, the enhanced controller successfully kept internal humidity levels at or above 70% even when the surrounding humidity fell to 25–27%. For example, when the humidity dropped below the threshold at 12:15 pm, the water pump ran for a calculated 10 minutes, then waited 30 minutes before the next sensing interval. Similarly, the controller is able to keep temperature in the range of 24 to 27 ºC as shown in Fig. 12. In order to ensure appropriate and effective control cycles, the DHT22 sensor subsequently updated the ambient parameters.

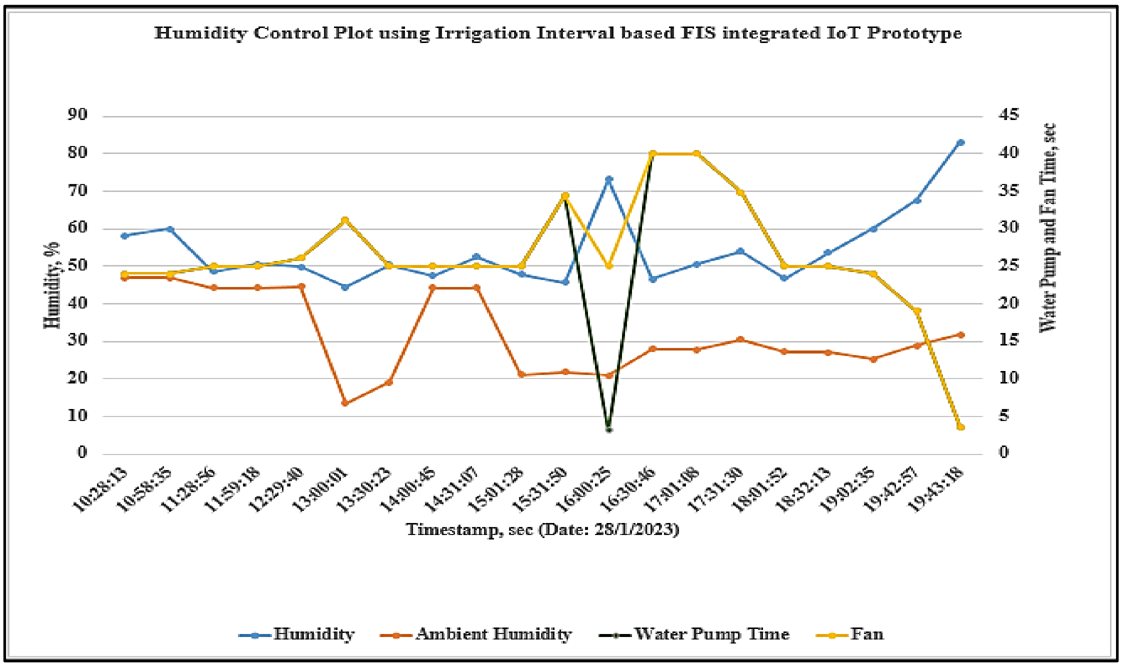

Fig. 11. Humidity control plot using Irrigation Interval based FIS integrated IoT prototype for a day

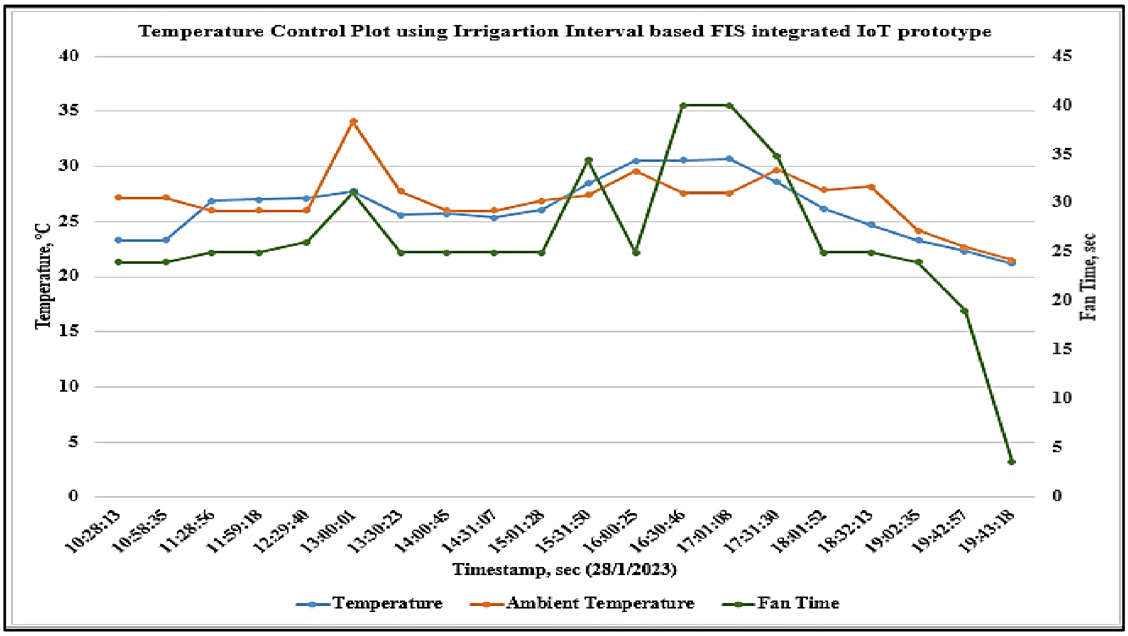

Fig. 12. Temperature control plot using Irrigation Interval based FIS integrated IoT prototype for a day

Fig. 13 illustrates how this control tweak dramatically decreased water consumption. With the interval-based FIS algorithm, the average daily water consumption dropped from 172 litres with the original FIS-only prototype to 34 litres. In particular, the amount of water used over the course of five days was 40 L, 40 L, 30 L, 30 L, and 30 L, respectively. This indicates that the water-use efficiency of the Irrigation Interval–based FIS controller was five times higher than that of the original FIS system.

To assess the efficiency of the Irrigation Interval-based FIS, a statistical test comparing water use per day between the baseline FIS and the proposed one was done for five representative operating days. The amount of water used by the baseline FIS is 172 ± 52.63 L/day, while the amount of water used by the proposed FIS is 34 ± 5.48 L/day, which resulted in an 80.23% decrease in water use. This decrease was found to be statistically significant based on Welch's independent samples t-test at a level of 5.83 with a degree of freedom of 4.1 ($p = 0.004$). To support the finding without making assumptions about the population distribution, the Mann-Whitney U test was done, and it showed $U = 0$ and $p = 0.008$. The effect size was also found to be extremely high ($d = 3.69$), indicating that the observed change is not caused by random variations.

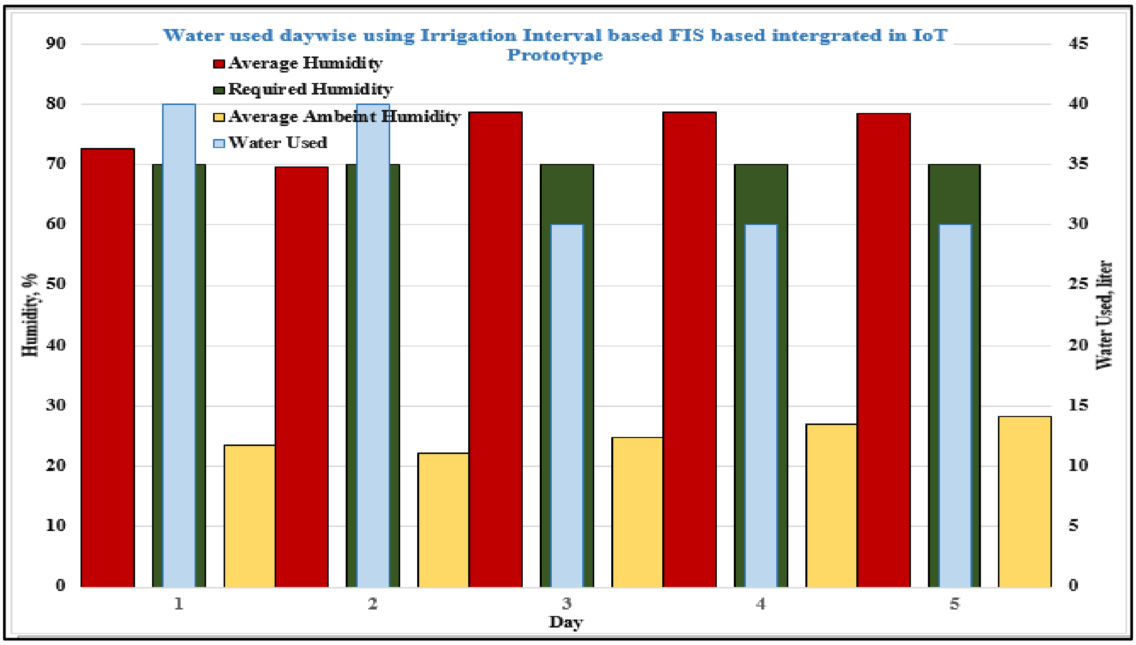

Fig. 13 Water used per day using Irrigation Interval based FIS integrated in IoT prototype

4.1 Common Problems and Solutions During Implementation

Several practical issues were encountered during the implementation of the FIS-based IoT prototype:

- Water Pump Compatibility: The initially used AC aqua motor failed to effectively drip water onto the gunny sheets. It was replaced with a DC-powered water pump for efficient operation.
- Reverse Current Issue: The high voltage load on the DC motor led to reverse current flow in the circuit. This was resolved by replacing the standard relay with an optocoupler relay circuit to prevent backflow.
- Insufficient Airflow: The mushroom unit could not be adequately cooled by the original AC cooling fan due to insufficient airflow. It was swapped out for an 85W cooling fan with more capacity.

- Sensor Failures: Manual connection inspection was necessary due to sporadic sensor faults. In the event of a hardware breakdown, an alarm mechanism was built in to transfer the system to manual mode.
- Power Outages: It was suggested that an Insulated Gate Bipolar Transistor (IGBT) be used to transfer the power supply to a battery backup mode in order to handle ESP32 controller shutdowns during power outages.
- Fuzzy Rule Adjustment: In order to achieve the best control during prototype testing, the fuzzy rule basis of the FIS system was experimentally changed.
- Pipe Blockage: Gunny sheet fibers made it easy for dripping holes in plastic pipes to clog. The water flow has to be maintained with regular cleaning.

5 Conclusion

This paper presented a temperature and humidity controlling system using IoT and fuzzy logic technology with irrigation interval planning for the outdoor oyster mushroom cultivation module. The suggested plan successfully addresses the two major challenges facing outdoor mushroom farming, namely, difficulty in controlling environmental parameters and inefficient management practices. Through the use of a sensor, a Mamdani FIS, and interval irrigation, the system is able to provide a smart way to regulate microclimates.

Based on experimental verification conducted for a duration of 17 days, the device was able to sustain the desired temperature range (24–27 °C) and humidity level (more than 70%). The reliability of the device was confirmed through statistical evaluation, which revealed consistency and dependability of the system with minimal deviations and a small standard deviation.

Another important accomplishment of this study was the implementation of the irrigation interval-based control strategy that managed to reduce water wastage due to the constant running of the pump. With this new arrangement, water consumption was greatly reduced, amounting to an 80% reduction in consumption without compromising the environmental requirements.

Taking everything into account, the suggested design is indeed a viable alternative at both lower costs and higher efficiencies. Especially considering the rural environment, the system has enormous possibilities in increasing efficiency, decreasing resource usage, and even generating income.

Nevertheless, there are some limitations that need to be considered. Firstly, the experiment lasted for a short period of time, while both baseline and proposed control schemes were tested during different periods. Despite the fact that the system worked in stable operating conditions during the test, a longer test period could confirm system robustness more reliably. Secondly, the prototype was tested only in one experiment site (ICAR-IIHR). Thus, the applicability of the system in various locations might be questionable. Thirdly, the research did not consider season changes, so it is necessary to estimate the system's performance in the different seasons. Lastly, the system uses DHT22 temperature and humidity sensors. Although they are inexpensive and popular sensors for IoT devices, their precision is limited by ±2–5% RH at high humidity levels.

The future scope of work in research includes the conduct of long-term and multiple-season assessments in varied geographical locations to further enhance the validation of the robustness and scalability of the proposed system. The modifications include the implementation of mobile-enabled controls, the application of machine learning techniques for predictive environment controls, and the inclusion of other sensing parameters such as the light intensity level, CO_2 levels, and the moisture content of the substrate material.

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