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Design And Implementation of an Arduino Based Automated Nutrient Control System For Hydroponic Tomato Cultivation Using Mamdani Fuzzy Logic

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Abstract

Achieving optimal growth and yield in hydroponic tomato farming demands strict control over nutrient composition and environmental factors. To support efficient physiological functions such as photosynthesis, transpiration, and nutrient uptake key parameters including nutrient solution pH, ambient temperature, and water levels must remain within specific thresholds. Relying on manual control frequently leads to delayed responses against environmental shifts, causing inconsistent plant performance. Consequently, this research focuses on developing an automated nutrient control system tailored for hydroponic tomatoes, leveraging Mamdani Fuzzy Logic embedded in an Arduino microcontroller. Input data from pH, temperature, water level, and light intensity sensors undergoes fuzzification, rule-based inference, and centroid defuzzification. Based on these processes, the system generates control signals to adjust fan speeds and solenoid valve durations, ensuring environmental stability. Experimental findings indicate that the proposed system adapts effectively to parameter variations, offering smoother control than traditional threshold-based methods. Ultimately, this Mamdani fuzzy-based approach significantly stabilizes the hydroponic environment while minimizing the need for manual intervention. **Keywords:** *Mamdani Fuzzy Logic, hydroponics, Arduino, control system, tomato cultivation*

INTRODUCTION

Smart farming and precision agriculture have profoundly altered contemporary agricultural methodologies, especially inside controlled environment cultivation systems. Among these techniques, hydroponic cultivation particularly the fertilizer Film Technique (NFT) has garnered heightened interest owing to its efficient water usage, superior fertilizer distribution, and increased crop yield. The efficacy of hydroponic systems is significantly contingent upon the maintenance of appropriate environmental conditions, encompassing pH stability, nutrient equilibrium, and water accessibility. Minor variations in these parameters might adversely impact plant growth performance and diminish crop quality.

Various environmental elements, including pH level, temperature, and water availability, are essential in influencing plant growth in hydroponic solutions. Prior research has demonstrated that automated control methods can markedly enhance the stability of certain parameters. Chen et al. (2022) established that fuzzy logic controllers offer superior regulation of hydroponic environmental factors relative to traditional control methods. Nasution et al. (2023) emphasized that the use of fuzzy logic into hydroponic control systems facilitates adaptive modifications of pH and other environmental factors, thus enhancing plant development conditions. These findings underscore the significance of sophisticated control systems for sustaining optimal nutrient conditions in hydroponic agriculture.

Traditional hydroponic control systems often depend on set threshold mechanisms, wherein actuators are engaged upon beyond predetermined limitations. Despite their relative ease of implementation, these systems frequently exhibit inflexibility in accommodating progressive environmental changes or sensor uncertainty. Consequently, these methodologies may yield erratic control responses. To mitigate this problem, fuzzy logic control has been extensively investigated as an alternative method. Agustian et al. (2022) indicated that the Mamdani Fuzzy Inference System (FIS) offers more seamless and adaptable control in NFT hydroponic systems than binary threshold approaches. Moreover, Prasetya et al. (2019) shown that Mamdani fuzzy control can improve the stability of hydroponic tomato growing by more successfully simulating the nonlinear interactions among environmental factors.

The amalgamation of the Internet of Things (IoT) with advanced control methodologies enhances the surveillance and automation functionalities of hydroponic systems. IoT-based technologies provide instantaneous data collection, remote surveillance, and automated activation. Untoro and Hidayah (2022) created an IoT-based monitoring and control system for plant cultivation, demonstrating enhanced operational efficiency and system responsiveness. Nugraha and Novantara (2025) proposed that integrating IoT architecture with fuzzy logic algorithms enhances nutrient management accuracy and improves remote decision-making procedures. These studies illustrate the increasing significance of IoT technologies in facilitating precision agriculture applications.

Furthermore, contemporary greenhouse automation increasingly utilizes sophisticated closed-loop control systems that continuously monitor and regulate environmental conditions. Walczuch et al. (2022) highlighted the significance of integrating closed-loop control systems with artificial intelligence to facilitate adaptive environmental management in greenhouse agriculture. Zeping et al. (2026) indicated that intelligent environmental control systems featuring real-time anomaly detection and energy-efficient automation enhance system stability and decrease operational expenses.

Notwithstanding these gains, numerous research gaps persist in the ongoing development of hydroponic automation systems. Many current research concentrate on monitoring or regulating a singular environmental parameter, such as pH or nutrient concentration, neglecting the interplay of numerous environmental variables (Al Tahtawi & Kurniawan, 2020). Secondly, certain implementations emphasize monitoring functions over adaptive control methods, thereby constraining the system's ability to adjust dynamically to environmental fluctuations (Widodo et al., 2022). Third, although fuzzy Sugeno methods have been applied in certain hydroponic systems like the Deep Flow Technique (DFT) (Dani et al., 2023), Mamdani-based fuzzy control is better appropriate for rule-based agricultural decision-making because of its intuitive language reasoning foundation.

Kurniasari et al. (2025) recently developed an intelligent IoT-based hydroponic automation system employing fuzzy logic for multi-parameter decision-making support. Nonetheless, additional study is necessary to create a comprehensive Mamdani-based control system that can concurrently regulate many environmental factors within a nutrient film technique hydroponic system. The incorporation of pH level, temperature, water level, and light intensity into a cohesive closed-loop control system is notably constrained in current research.

This paper proposes the design and implementation of an IoT-based hydroponic monitoring and control system employing the Mamdani Fuzzy Inference System. The suggested system modulates ambient conditions by modifying actuator functions, such as fan speed and solenoid valve activation, according to four input parameters: pH level, temperature, water level, and light intensity. This research is innovative due to the incorporation of a structured fuzzy rule-based control system with real-time IoT monitoring, resulting in a more flexible and stable hydroponic automation system.

The main aim of this project is to create an intelligent hydroponic control system that increases stability, promotes response to environmental changes, and facilitates effective nutrient management in NFT hydroponic production. The suggested system aims to enhance precision agriculture by delivering a strong, transparent, and scalable control architecture appropriate for contemporary smart farming applications.

METHODS

An intelligent hydroponic nutrient control system based on Mamdani Fuzzy Logic is engineered, deployed, and validated in this R&D framework. The R&D strategy combined theoretical modeling with actual prototyping to ensure the system works in real-world hydroponic conditions. Literature synthesis, requirement specification, architectural design, fuzzy modeling, simulation, hardware integration, and performance benchmarking were sequentially performed. Recent IoT-based hydroponic and greenhouse experiments show that this structure mimics smart agriculture automation methods (Kurniasari *et al.,* 2025; Walczuch, 2022; Zeping, 2026).

First, a thorough literature analysis identified environmental and nutrient parameters essential to hydroponic plant growth. Based on previous investigations (Wijaya *et al.,* 2025; Santos, 2021), pH, temperature, water level, and light intensity were identified as critical input variables. Due to their importance in nutrient bioavailability and plant physiology, these criteria were highlighted. Requirement analysis determined suitable growth thresholds, sensor measurement ranges, and technical specs. To improve data accuracy and reduce measurement uncertainty, sensor calibration processes and reliability assessments were integrated using confidence analysis techniques from previous research.

For adaptive, automated hydroponic regulation, a closed-loop control architecture was created. The design has three layers: data collecting (pH, temperature, water level, and light intensity sensors), processing (microcontroller executing the Mamdani fuzzy algorithm), and actuation. For real-time monitoring, remote oversight, and data logging, an IoT connectivity module was embedded. The closed-loop configuration provides continuous feedback and dynamic output modifications, boosting system response to environmental unpredictability.

The Fuzzy Logic Toolbox was used to create the FIS in MATLAB. pH was assigned Acidic, Neutral, and Alkaline, temperature Cold, Moderate, and Hot, water level Low, Medium, and Full, and light intensity Dim, Normal, and Bright. The output variables were fan speed (Low, Medium, High) and solenoid valve duration (Off, Short, Long). We used triangular and trapezoidal membership functions to represent gradual state shifts. A solid IF–THEN rule base encoded professional agronomic nutrient management knowledge. The Mamdani MIN–MAX technique with centroid-based defuzzification ensured smooth and stable control signal generation in the inference engine.

Environmental situations such fertilizer shortages, pH aberrations, and multi-parameter disturbances were simulated in MATLAB to evaluate system performance. Stability, control smoothness, and adaptability were assessed using output surface visualization and transient response analysis. After simulation validation, the fuzzy algorithm was translated to a microcontroller for hardware deployment. The integrated prototype was tested in a hydroponic setting for regulatory precision, reaction latency, and operational durability. Performance measurements were compared to threshold-based controllers to measure adaptive decisionmaking and system efficiency improvements.

1. Formation of Fuzzy Sets and Input Variables

During the first step of design, all input and output variables were turned into fuzzy sets. The study used four input variables: pH, temperature, water level, and light intensity. Each of these was described in a different way using words. For example, pH was divided into Acidic, Neutral, and Alkaline; temperature was divided into Cold, Moderate, and Hot; water level was divided into Low, Medium, and Full; and light intensity was divided into Dim, Normal, and Bright. The system controls the speed of the fan (Low, Medium, High) and the length of time the solenoid valve stays open (Off, Short, Long). These fuzzy set definitions were made to take into account sensor uncertainty and changes in the environment. This lets the Mamdani inference engine make control decisions that adapt to the real conditions in the hydroponic system.

Table 1. Fuzzy sets and linguistic variables for system inputs and outputs

Type	Variable	Fuzzy Set	Domain	[a, b, c, d]
Input	Ph	Sour	0 - 15	[0 0 4.5 6.5]
		Neutral		[4.5 6.5 8]
		Alkaline		[6 8 15 15]
Input	Light Intensity	Bright	50 – 250	[50 50 110 180]
		Normal		[160 190 220]
		Dim		[200 230 250 250]
Input	Temperature (℃)	Cold	15 – 40	[0 0 22 24]
		Normal		[22 24 30 32]
		High		[28 32 40 40]
Input	Water Level	Little	0 - 100	[0 0 40]
		Enough		[30 50 70]
		Full		[60 100 100]

Table 2. Variable Output Membership Function

Type	Variable	Fuzzy Set	Domain Conversation	[a, b, c, d]
Output	Fan Speed	Low	0 – 100	[0, 25, 50]
		Medium		[40, 60, 80]
		High		[70, 85, 100]

2. Hardware Components

The automation framework includes several pieces of hardware that work together to make monitoring and control easier:

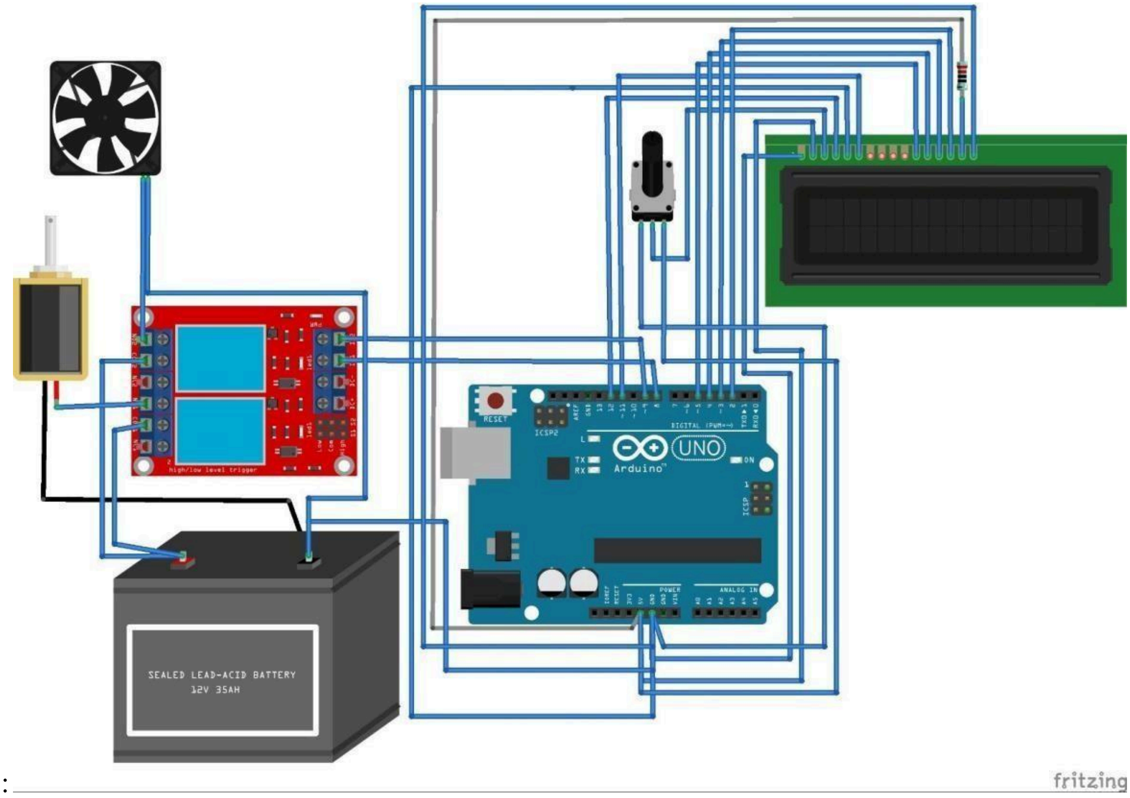


Figure 1. *Block diagram of the automated hydroponic nutrient control system*

1. **Arduino Uno:** The Arduino Uno is the main control unit of the system. It is in charge of collecting data, making decisions, and controlling the actuators. It gets both analog and digital signals from a number of sensors, interprets these inputs with the built-in Mamdani Fuzzy Logic algorithm, and then sends out the right orders. Its open-source design, enough I/O capacity, and ability to work with different peripheral modules make it a good choice for real-time control applications in hydroponic automation systems.
2. **pH sensor:** The pH sensor is used to keep an eye on the acidity or alkalinity of the nutrient solution in the hydroponic reservoir all the time. To make sure that plant roots can absorb nutrients well, it is important to keep the pH level in the right range. The sensor sends out analog voltage signals that are directly related to the concentration of hydrogen ions. The

microcontroller then turns these signals into digital values for further processing and control modification.

3. **Temperature sensor (LM35 or something similar):** The temperature sensor keeps an eye on the temperature of the air around the hydroponic system. The LM35 and other devices like it give a linear output voltage that is directly related to temperature in degrees Celsius. This makes it easy to get accurate readings without having to do any further calibration. Accurate temperature monitoring helps with thermal regulation measures, which keep plants from being too hot and keep the conditions good for physiological functions like photosynthesis and transpiration.
4. **Moisture sensor (FC-28 or similar):** This sensor is used to find out how much water is in the growing medium. The sensor uses its probes to measure changes in electrical conductivity or resistance to figure out how wet the substrate is. This information is very important for managing irrigation since it makes sure that plants get enough water without getting too much, which could cause root hypoxia or nutritional imbalance.
5. **Solenoid valves:** Solenoid valves are electromechanical actuators that control the flow of nutrient solution through the hydroponic system. The valve opens or closes to change the length and frequency of nutrient delivery when control signals from the microcontroller (usually through a relay link) turn it on. This regulated flow system lets you dose exactly and lets you change the way you water based on fuzzy inference results.
6. **Cooling fan:** The cooling fan is a part of the thermal regulation system that keeps the temperature in the growing region stable. When the temperature rises, the fan gets signals to turn on and increases the flow of air to get rid of extra heat. This changing ventilation system helps keep the environment stable and stops temperature changes that could hurt plant growth.
7. **Display module:** The display module, which is usually a 16×2 LCD, shows important system metrics like pH levels, temperature measurements, and moisture status in real time. The display makes the system more transparent by showing processed data in a way that is easy for users to understand. This lets operators keep an eye on environmental conditions and manage reactions without using any outside monitoring devices.

All sensing elements send out continuous analog voltage signals that are based on the physical parameters that are being monitored. These analog outputs are connected to the Arduino's analog input channels, where the built-in analog-to-digital converter (ADC) samples and digitizes them. The digitized data are then scaled and calibrated to show useful physical units before the embedded Mamdani Fuzzy Logic control system processes them. This process of acquiring and converting signals makes sure that parameters are evaluated correctly in real time and that decisions can be made reliably inside the intelligent control framework.

3. Input and Output Variables

The fuzzy control architecture has four input variables and two output variables. Each variable is described in words using triangular or trapezoidal membership functions. Based on the average operating ranges for growing hydroponic tomatoes, we set the universe of discourse for each parameter.

Inputs:

1. pH Level

The pH parameter measures how acidic a nutrient solution is, with a range of 0 to 15.

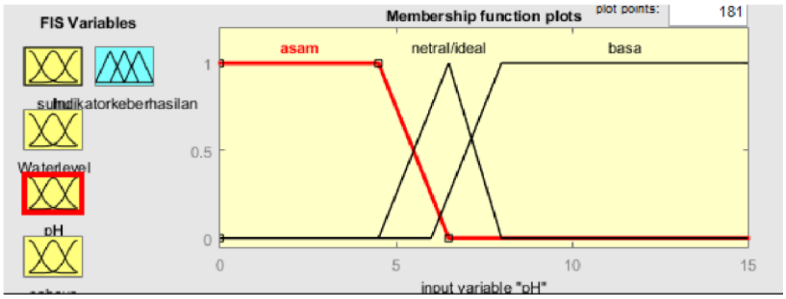


Figure 2. Membership function graph of the pH variable in the fuzzy system

Table 3. Variable Output Membership Function

Fuzzy Set	**Type**	**Domain [a b c d]**
Sour	Trapezoidal	[0 0 4.5 6.5]
Neutral	Triangular	[4.5 6.5 8]
Alkaline (Wets corrected)	Trapezoidal	[6 8 15 15]

2. Light Intensity

Illumination levels, measured in lux (50–250 range), have an effect on how plants make food through photosynthesis.

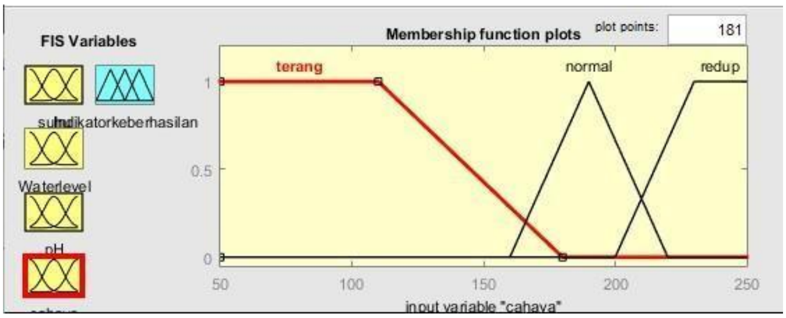


Figure 3. Membership function graph of the light intensity variable in the fuzzy system

Table 4. Parameters of the light intensity fuzzy sets

Fuzzy Set	**Type**	**Domain [a b c d]**
Bright	Trapezoidal	[50 50 110 180]
Normal	Triangular	[160 190 220]
Dim	Trapezoidal	[200 230 250 250]

3. Temperature (°C)

The temperature of the environment, which is very important for plant metabolism, is kept between 15 and 40 degrees Celsius.

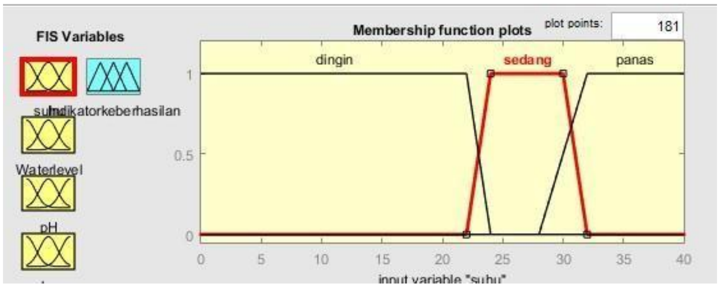


Figure 4. Membership function graph of the temperature variable in the fuzzy system

Table 5. Parameters of the temperature fuzzy sets, including the trapezoidal membership function type and their respective domain boundaries

Fuzzy Set	**Type**	**Domain [a b c d]**
Cold	Trapezoidal	[0 0 22 24]
Normal	Trapezoidal	[22 24 30 32]
High	Trapezoidal	[28 32 40 40]

4. Water Level (%)

To show how available the solution is, the reservoir water status is put on a scale from 0 to 100%.

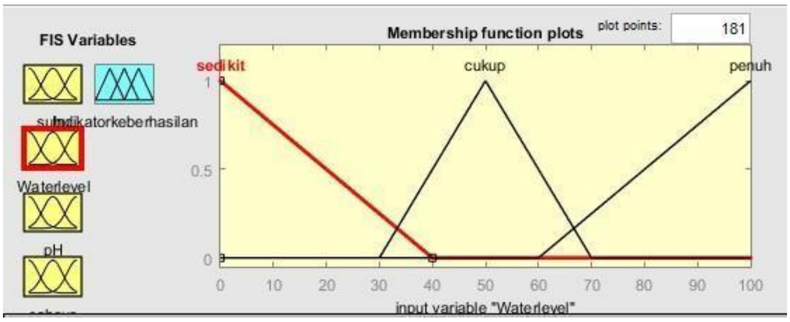


Figure 5. Membership function graph of the water level variable in the fuzzy system

Table 6. Parameters of the water level fuzzy sets

Fuzzy Set	**Type**	**Domain**

Little	Triangular	[0 0 40]
Enough	Triangular	[30 50 70]
Full	Triangular	[60 100 100]

Each input is split into three fuzzy sets, such low, medium, and high, or dry, normal, and moist.

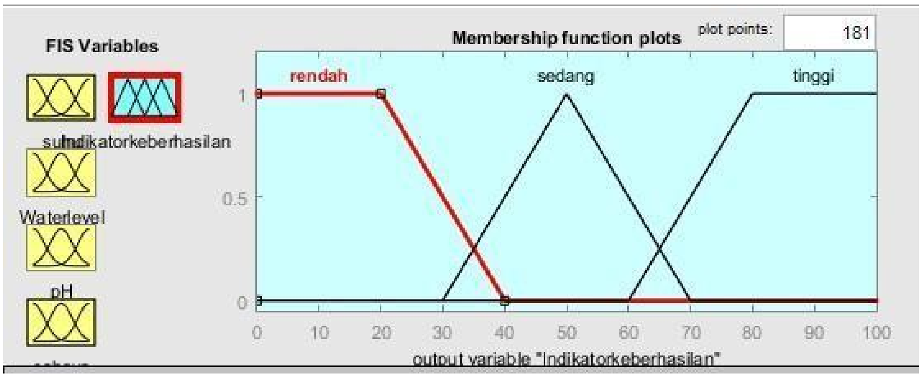


Figure 6. Membership function graph of the Nutrient Pump Duration output variable

Output Fan Speed using for :

Table 7. Fuzzy sets and linguistic labels for input and output variables

Fuzzy Set	**Function**	**Domain**
Low	**trapmf**	**[0 0 30 50]**
Medium	**trimf**	**[30 50 70]**
High	**trapmf**	**[60 80 100 100]**

One of the output variables of the proposed fuzzy inference system is the Cooling Fan Speed. This variable shows how strong the airflow regulation is that is utilized to keep the temperature in the hydroponic growing area stable. The control output is a percentage from 0% to 100%, with higher values meaning the fan will spin faster.

4. Mamdani Fuzzy Logic Model

There are four steps to using the Mamdani fuzzy inference method: Fuzzification takes exact sensor inputs and turns them into fuzzy membership degrees that the inference engine can understand. This study processes four inputs—pH, temperature, water level, and light intensity—each mapped to language concepts by triangular or trapezoidal membership functions. For example, pH can be Acidic, Neutral, or Alkaline; temperature can be Cold, Moderate, or Hot; water level can be Low, Medium, or Full; and light intensity might be Dim, Normal, or Bright.

There were three levels of pH: acidic, neutral, and alkaline.

- The temperature was divided into three groups: cold, moderate, and hot.

- The level of water was shown as Low, Medium, and High. ● There were three levels of light intensity: dim, normal, and bright. b. Making the Rule Base

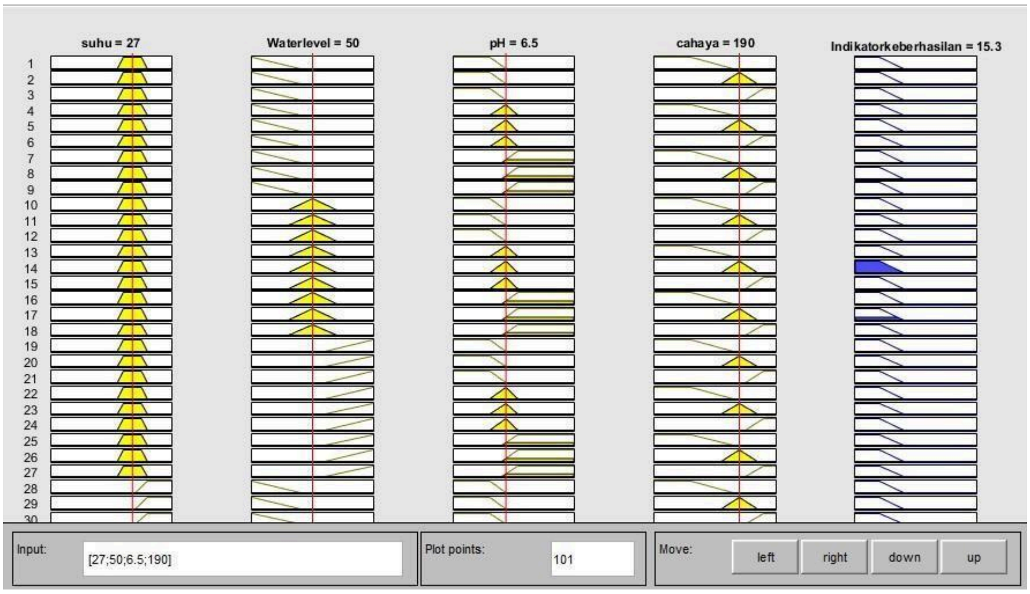
An extensive IF–THEN rule foundation was developed to encapsulate agronomic knowledge for hydroponic management. These principles take into account nonlinear interactions between environmental factors, which makes it possible to make control decisions that take the situation into account. For example, when the pH is acidic, the temperature is cold, the water level is low, and the light is bright, the system sends out a low control signal. The whole set of rules (81 combinations) makes sure that all conceivable input state permutations are covered.

1. IF pH Acidic AND Temperature Cold AND Water Low AND Bright Light → TGSI Low
2. IF pH Acidic AND Temperature Cold AND Water Low AND Normal Light → TGSI Low
3. IF pH Acidic AND Temperature Cold AND Water Low AND Dim Light → TGSI Low
4. IF pH Acidic AND Temperature Cold AND Medium Water AND Bright Light → TGSI Low
5. IF pH Acidic AND Temperature Cold AND Medium Water AND Normal Light → TGSI Medium
6. IF pH Acidic AND Temperature Cold AND Medium Water AND Dim Light → TGSI Low
7. IF pH Acidic AND Temperature Cold AND Full Water AND Bright Light → TGSI Low
8. IF pH Acidic AND Temperature Cold AND Full Water AND Normal Light → TGSI Low
9. IF pH Acidic AND Temperature Cold AND Full Water AND Dim Light → TGSI Low
10. IF pH Acidic AND Normal Temperature AND Water Low AND Bright Light → TGSI Low
11. IF pH Acidic AND Normal Temperature AND Water Low AND Normal Light → TGSI Medium
12. IF pH Acidic AND Normal Temperature AND Water Low AND Dim Light → TGSI Low
13. IF pH Acidic AND Normal Temperature AND Medium Water AND Bright Light → TGSI Medium
14. IF pH Acidic AND Normal Temperature AND Medium Water AND Normal Light → TGSI Medium
15. IF pH Acidic AND Normal Temperature AND Medium Water AND Dim Light → TGSI Medium
16. IF pH Acidic AND Normal Temperature AND Full Water AND Bright Light → TGSI Low
17. IF pH Acidic AND Normal Temperature AND Full Water AND Normal Light → TGSI Medium

18. IF pH Acidic AND Normal Temperature AND Full Water AND Dim Light → TGSI Low
19. IF pH Acidic AND Hot Temperature AND Water Low AND Bright Light → TGSI Low
20. IF pH Acidic AND Hot Temperature AND Water Low AND Normal Light → TGSI Low
21. IF pH Acidic AND Hot Temperature AND Water Low AND Dim Light → TGSI Low
22. IF pH Acidic AND Hot Temperature AND Medium Water AND Bright Light → TGSI Medium
23. IF pH Acidic AND Hot Temperature AND Medium Water AND Normal Light → TGSI Medium
24. IF pH Acidic AND Hot Temperature AND Medium Water AND Dim Light → TGSI Low
25. IF pH Acidic AND Hot Temperature AND Full Water AND Bright Light → TGSI Low
26. IF pH Acidic AND Hot Temperature AND Full Water AND Normal Light → TGSI Low
27. IF pH Acidic AND Hot Temperature AND Full Water AND Dim Light → TGSI Low
28. IF pH Neutral AND Temperature Cold AND Water Low AND Bright Light → TGSI Low
29. IF pH Neutral AND Temperature Cold AND Water Low AND Normal Light → TGSI Medium
30. IF pH Neutral AND Temperature Cold AND Water Low AND Dim Light → TGSI Low
31. IF pH Neutral AND Temperature Cold AND Medium Water AND Bright Light → TGSI Medium
32. IF pH Neutral AND Temperature Cold AND Medium Water AND Normal Light → TGSI High
33. IF pH Neutral AND Temperature Cold AND Medium Water AND Dim Light → TGSI Medium
34. IF pH Neutral AND Temperature Cold AND Full Water AND Bright Light → TGSI Medium
35. IF pH Neutral AND Temperature Cold AND Full Water AND Normal Light → TGSI Medium
36. IF pH Neutral AND Temperature Cold AND Full Water AND Dim Light → TGSI Low
37. IF pH Neutral AND Normal Temperature AND Water Low AND Bright Light → TGSI Medium
38. IF pH Neutral AND Normal Temperature AND Water Low AND Normal Light → TGSI Medium
39. IF pH Neutral AND Normal Temperature AND Water Low AND Dim Light → TGSI Medium
40. IF pH Neutral AND Normal Temperature AND Medium Water AND Bright Light → TGSI High
41. IF pH Neutral AND Normal Temperature AND Medium Water AND Normal Light → TGSI High

42. IF pH Neutral AND Normal Temperature AND Medium Water AND Dim Light → TGSI High
43. IF pH Neutral AND Normal Temperature AND Full Water AND Bright Light → TGSI Medium
44. IF pH Neutral AND Normal Temperature AND Full Water AND Normal Light → TGSI Medium
45. IF pH Neutral AND Normal Temperature AND Full Water AND Dim Light → TGSI Medium
46. IF pH Neutral AND Hot Temperature AND Water Low AND Bright Light → TGSI Low
47. IF pH Neutral AND Hot Temperature AND Water Low AND Normal Light → TGSI Medium
48. IF pH Neutral AND Hot Temperature AND Water Low AND Dim Light → TGSI Low
49. IF pH Neutral AND Hot Temperature AND Medium Water AND Bright Light → TGSI Medium
50. IF pH Neutral AND Hot Temperature AND Medium Water AND Normal Light → TGSI High
51. IF pH Neutral AND Hot Temperature AND Medium Water AND Dim Light → TGSI Medium
52. IF pH Neutral AND Hot Temperature AND Full Water AND Bright Light → TGSI Low
53. IF pH Neutral AND Hot Temperature AND Full Water AND Normal Light → TGSI Medium
54. IF pH Neutral AND Hot Temperature AND Full Water AND Dim Light → TGSI Low
55. IF pH Alkaline AND Temperature Cold AND Water Low AND Bright Light → TGSI Low
56. IF pH Alkaline AND Temperature Cold AND Water Low AND Normal Light → TGSI Low
57. IF pH Alkaline AND Temperature Cold AND Water Low AND Dim Light → TGSI Low
58. IF pH Alkaline AND Temperature Cold AND Medium Water AND Bright Light → TGSI Low
59. IF pH Alkaline AND Temperature Cold AND Medium Water AND Normal Light → TGSI Low
60. IF pH Alkaline AND Temperature Cold AND Medium Water AND Dim Light → TGSI Low
61. IF pH Alkaline AND Temperature Cold AND Full Water AND Bright Light → TGSI Low
62. IF pH Alkaline AND Temperature Cold AND Full Water AND Normal Light → TGSI Low
63. IF pH Alkaline AND Temperature Cold AND Full Water AND Dim Light → TGSI Low

64. IF pH Alkaline AND Normal Temperature AND Water Low AND Bright Light → TGSI Low
65. IF pH Alkaline AND Normal Temperature AND Water Low AND Normal Light → TGSI Low
66. IF pH Alkaline AND Normal Temperature AND Water Low AND Dim Light → TGSI Low
67. IF pH Alkaline AND Normal Temperature AND Medium Water AND Bright Light → TGSI Low
68. IF pH Alkaline AND Normal Temperature AND Medium Water AND Normal Light → TGSI Medium
69. IF pH Alkaline AND Normal Temperature AND Medium Water AND Dim Light → TGSI Low
70. IF pH Alkaline AND Normal Temperature AND Full Water AND Bright Light → TGSI Low
71. IF pH Alkaline AND Normal Temperature AND Full Water AND Normal Light → TGSI Low
72. IF pH Alkaline AND Normal Temperature AND Full Water AND Dim Light → TGSI Low
73. IF pH Alkaline AND Hot Temperature AND Water Low AND Bright Light → TGSI Low
74. IF pH Alkaline AND Hot Temperature AND Water Low AND Normal Light → TGSI Low
75. IF pH Alkaline AND Hot Temperature AND Water Low AND Dim Light → TGSI Low
76. IF pH Alkaline AND Hot Temperature AND Medium Water AND Bright Light → TGSI Low
77. IF pH Alkaline AND Hot Temperature AND Medium Water AND Normal Light → TGSI Low
78. IF pH Alkaline AND Hot Temperature AND Medium Water AND Dim Light → TGSI Low
79. IF pH Alkaline AND Hot Temperature AND Full Water AND Bright Light → TGSI Low
80. IF pH Alkaline AND Hot Temperature AND Full Water AND Normal Light → TGSI Low
81. IF pH Alkaline AND Hot Temperature AND Full Water AND Dim Light → TGSI Low



Input: [27;50;6.5;190]

Plot points: 101

Figure 7. Fuzzy inference rule viewer showing the input values

c. Fuzzyfication Input Variable pH

(6.3):

Domain Neutral:

[5.5, 6.5, 7.5]

$$\mu Neutral(6.3) = \frac{6.3-5.5}{6.5-5.5} \quad \frac{0.8}{1} \quad = \quad = 0.8$$

Temperature(26°C)

Domain Medium:

[20, 25, 30]

$$\mu Normal(26) = \frac{30-26}{30-25} \quad \frac{4}{5} = = 0.8$$

Water Level(55%) Domain

Full:

[40, 60, 80]

$$\mu Medium(55) = \frac{55-40}{60-40} \quad \frac{15}{20} \quad = \quad = 0.75$$

Light Intesity(190)

Domain Normal Intensity::

[160, 190, 220]

$$\mu Normal(180) = \frac{190-160}{190-160} \quad \frac{30}{30} \quad = \quad = 1$$

Active Rules:

IF pH Neutral
AND Normal Temperature
AND Medium Water
AND Normal Light THEN
TGSI High

With Operator MIN:

$$\alpha = min(0.8,0.8,0.75,1)$$

$$\alpha = 0.75$$

Output Area:

Domain High [60,80,100]

a. Intersection point on the rising edge:

$$0.75 = \frac{Z-60}{80-60}$$

$$0.75 = \frac{Z-60}{20}$$

$$Z - 60 = 15$$

$$Z = 75$$

b. Intersection point on the falling edge:

$$0.75 = \frac{100-Z}{100-80}$$

$$0.75 = \frac{100-Z}{20}$$

$$100 - Z = 15$$

$$Z = 85$$

Active AREA:

$$75 \leq Z \leq 85$$

CENTROID

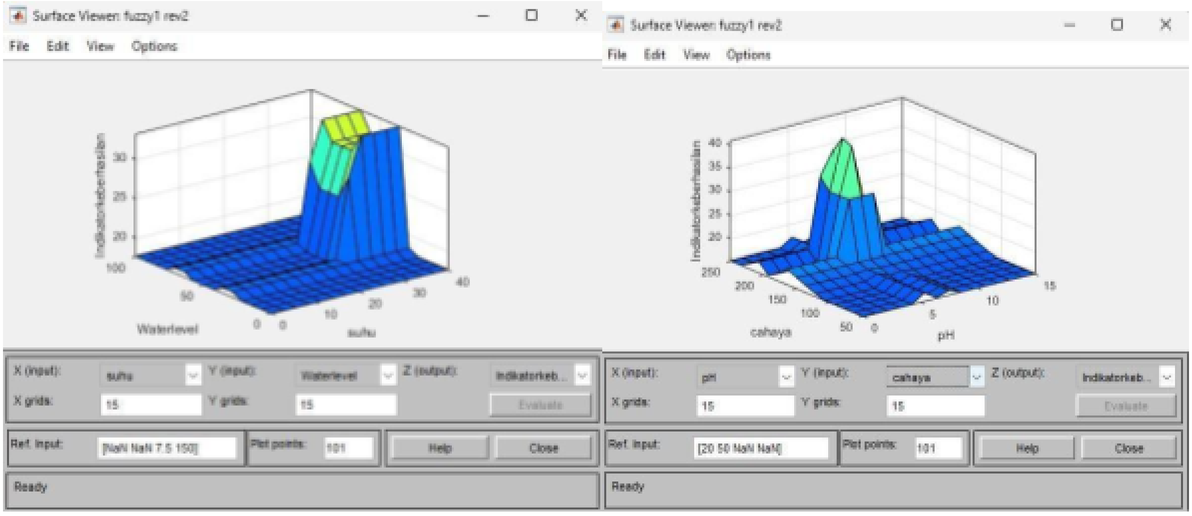
$$Z^* = 80$$

Fuzzification is the process of changing clear sensor values into fuzzy membership values. This study used triangular and trapezoidal membership functions to define the language terms for the input variables: pH, temperature, and moisture.

The pH variable was split into three hazy groups: Acidic, Neutral, and Alkaline. We divided temperature into three groups: cold, moderate, and hot. We also divided moisture into three groups: low, medium, and high. The sensors sent back a crisp value, which was then put into one or more fuzzy sets with a particular level of membership.

This improvement makes the system better able to deal with uncertainty and slow changes in external factors, making it easier to use for later rule assessment and inference.

d. Defuzzification



X (input): suhu
Y (input): Waterlevel
Z (output): Indikatorkeb...
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 7.5 150]
Plot points: 101
Ready

X (input): pH
Y (input): cahaya
Z (output): Indikatorkeb...
X grids: 15
Y grids: 15
Ref. Input: [20 50 NaN NaN]
Plot points: 101
Ready

Figure 8. Surface viewer of the fuzzy inference system illustrating the defuzzification results using the centroid method, showing the relationship between input variables and the resulting crisp output values

Defuzzification is the last step in fuzzy inference, turning combined fuzzy outputs into clear actuator commands. This study uses the centroid method to find the center of gravity of combined membership functions in order to get exact output values. The resulting clear signals are in the form of PWM values, which directly control the speed of the fan and the length of time the solenoid valve stays open. This method makes sure that control actions happen slowly and steadily instead of suddenly switching, which makes environmental regulation more consistent.

5. Software Implementation

The fuzzy logic technique was put to use in the Arduino IDE environment, where the firmware does five main tasks. These tasks involve getting and calibrating sensor data, figuring out the membership degree, evaluating the rule base, defuzzifying the centroid, and sending a PWM signal to control the actuator. This structured software design makes sure that raw sensor data is translated in a systematic way into accurate control commands. This lets the microcontroller efficiently control the speeds of the fans and the lengths of the solenoid valves.

6. Testing and Evaluation

To validate the system, the prototype was put through a range of environmental tests, such as changes in pH, temperature, water level, and light intensity, while the actuator reactions were watched. To make sure that the fuzzy output decisions were logically consistent, they were verified against the expected rule-based results. The main performance criteria were control stability and reaction accuracy. These made sure that the system could manage changing situations without too much oscillation or delay.

RESULTS AND DISCUSSION

The automated fertilizer control system for growing tomatoes in hydroponics using Arduino and Mamdani Fuzzy Logic was successfully designed and put into use. This framework uses four environmental sensors—pH, temperature, water level, and light intensity—as input variables. It also controls the speed of the fan and the length of time the solenoid valve stays open as output actuators. System validation included both MATLAB simulations and realworld hardware tests to check how accurate the controls were and how quickly they responded to changes. The fuzzy inference engine interprets real-time sensor data well, creating actuator orders that follow established linguistic rules. The seamless integration of sensing, processing, and actuation modules exhibited dependable functionality under experimental conditions, showcasing stable performance and uniform control behavior. These results together show that the suggested approach for intelligent environmental control in hydroponic tomato farming is both technically feasible and useful in practice.

1. System Functional Results

Mamdani Fuzzy Logic was used to make the intelligent hydroponic control framework, which used an Arduino Uno as the main processing unit. This design works with a lot of different sensors, such as pH and temperature probes to check the acidity and temperature of the solution, a water level sensor to check the state of the reservoir, and a light intensity sensor to check the amount of light in the environment. A cooling fan and a solenoid valve control actuation. Fuzzy inference outputs control how these two parts work. During the experiments, the sensors sent real-time data to the microcontroller all the time. The Mamdani inference engine looked at the rule base to figure out what control actions to take once the predefined membership functions turned the acquired inputs into linguistic variables. Defuzzification used the Centroid method to get clear output numbers that showed the % of fan speed and the amount of time the solenoid valve opened. The method worked well to keep the environmental conditions in the right range for growing hydroponic tomatoes. For example, the solenoid valve stayed open for longer periods of time to fill the reservoir when the water level readings dropped below the "Enough" level. However, the valve stayed closed when the levels hit "Full." In the same way, changes in temperature caused corresponding changes in the fan: higher measurements increased airflow, while intermediate readings kept the baseline ventilation. This adaptive behavior shows that the system can control the surroundings based on the situation.

2. Fuzzy Inference Output

One experimental scenario used the following input circumstances to show how the system worked: pH = 4 (Acidic), Temperature = 25°C (Moderate), Water Level = 30% (Low), and

Light Intensity = Normal. After fuzzy inference and centroid defuzzification, the system made these commands for the actuators: Fan Speed = Medium (around 60% PWM), and Solenoid Valve Duration = Long opening. From a control logic point of view, these outputs match the encoded rule base exactly. A pH reading of 4 is well within the "Acidic" membership function, which has a high membership degree. This means that the environment needs to be changed to fix the problem. At the same time, a water level of 30% falls into the "Low" fuzzy set, which means that the reservoir is running low and needs to be filled again. So, the rule base tells the solenoid valve to stay open longer to bring the solution volume back to normal. The system doesn't use aggressive, binary responses; instead, it shares control effort depending on overlapping membership degrees, which is a key benefit of Mamdani fuzzy reasoning. The fan runs at a medium speed because the temperature input (25°C) is in the "Normal" membership range. Active cooling isn't necessary, but baseline airflow helps keep temperatures stable and prevents heat from building up in one area, which makes the system more energy efficient. This situation shows how the fuzzy inference framework turns linguistic rule interactions into smooth, quantitative actuator signals. The centroid defuzzification method finds the center of gravity across all the aggregated output membership functions. This makes sure that the final commands show how all the activated rules work together. This method looks at environmental states as a whole, which stops oscillatory behavior and cuts down on sudden actuator changes. This is different from inflexible threshold-based controllers. In the end, these results show that the Mamdani fuzzy controller can handle complicated interactions between parameters and give reliable, proportionate, and context-sensitive responses that are perfect for precision hydroponic farming. The system's intelligence comes not only from math, but also from how it uses language to understand shapes. It acts like a smart agronomist who makes small changes over time instead of reacting right away.

3. Hardware Measurement Results

Real-world measurements of actuator outputs showed that PWM duty cycles and voltage levels were very close to the fuzzy values that were calculated theoretically, with just small differences. The difference between the defuzzification results and the real actuator signals stayed within an acceptable error range (<5%), which showed that the Arduino firmware and driver circuitry were reliable. The speed at which the fan turned changed in direct proportion to the fuzzy output commands, and the solenoid valve opened and closed according to the calculated opening times. During state changes, there was no noticeable latency or instability, which shows how responsive the system is in real time and how strong the hardware is.

4. Performance Impact on Plant Control

In regulated operational settings, the fuzzy-logic-based automation kept environmental parameters much closer to the agronomic target ranges than when people were involved. This automatic system is useful because it keeps the pH, temperature, and water levels consistent, which are all important for the growth of tomatoes. Fuzzy-logic controllers are also more flexible than fixed-threshold controllers because they allow for progressive, proportional responses instead of sudden binary switching. This reduces the mechanical stress on actuators and makes the whole system last longer.

5. Discussion

The Mamdani fuzzy logic framework is especially useful for hydroponic control applications since agricultural parameters are always changing, nonlinear, and uncertain. pH, temperature, water level, and light intensity are some of the things that change all the time because of changes in the environment. Using linguistic variables like "Low," "Medium," and "High," you may immediately embed your domain knowledge and practical growing tips into the control rule base. This method lets agronomic reasoning be defined as organized mathematical inference, so there is no need for complicated, computer-intensive plant development models.

Compared to traditional threshold-based controllers, fuzzy logic makes actuators respond in a smoother and more flexible way. Instead of transitioning between two states quickly, the Mamdani inference engine looks at overlapping membership functions and combines them to create proportionate outputs through aggregation and centroid defuzzification. This means that actuator oscillations are kept to a minimum, mechanical wear on pumps and valves is decreased, and the overall stability of the system is improved. This progressive change between control states is especially helpful in hydroponic systems, where rapid changes to nutrient delivery or solution chemistry could cause root stress or physiological shock.

However, the accuracy and dependability of the system depend heavily on careful sensor calibration and well-thought-out membership functions. If the pH, temperature, or water level sensors are not calibrated correctly, the fuzzification step can be messed up, which could cause the wrong rules to be activated and bad control decisions to be made. So, in order to keep control accuracy, systematic calibration techniques and regular validation cycles are necessary. Also, the boundaries of membership functions must be based on real-world agronomic criteria. If the ranges are not clear, they could cause the actuator intensity levels to be too high, which could harm the plants.

Adding more input variables, including electrical conductivity (EC) or direct nutritional ion concentration measures, could improve the system's performance even further. If the rule base were expanded to include these factors, the controller would be able to mimic more complicated interactions in hydroponics. Adding more variables and rules will always make the computer work harder, but the trade-off leads to far better control resolution and adaptability to different environments. The results of this study show that the Arduino-based Mamdani fuzzy controller works well, gives consistent actuator responses, and is feasible for automating nutrient management in hydroponic tomato production. The system shows steady performance, the ability to make decisions that change based on the situation, and real-world usefulness for large-scale smart agriculture implementations.

CONCLUSION

Empirical evidence validates that the fuzzy controller maintains environmental and nutrient parameters within agronomically acceptable limits. The approach handles uncertainty, nonlinear interactions, and dynamic perturbations that are common in hydroponic situations very well by using language variable encoding and rule-based reasoning. Compared to regular threshold-based controllers, the Mamdani method makes actuator transitions smoother, reduces sudden switching artifacts, and makes the whole system more stable.

Using centroid-based defuzzification makes sure that the output is proportional and consistent, which makes it easy to change the speeds of the fans and the lengths of the solenoid valves in real time based on feedback from the environment. These results show that fuzzy logic is more than just a theory; it works in real life for scalable smart agriculture automation.

However, the effectiveness of the system still depends on precise sensor calibration and carefully designed membership functions. Potential improvements can include adding more metrics, such as electrical conductivity (EC), using IoT-enabled remote monitoring interfaces, and improving the fuzzy rule base with adaptive or hybrid intelligent optimization methods.

The suggested Mamdani fuzzy-based control framework is reliable, stable, and practical for automated nutrient management in hydroponic tomato growing. In this way, it is a scalable and usable solution that meets the changing needs of modern smart farming ecosystems.

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