

FUZZY LOGIC-CONTROLLED IOT SYSTEM FOR SMART PUBLIC TOILETS: DESIGN, IMPLEMENTATION, AND EVALUATION

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ABSTRACT

Efficient energy management in public facilities such as public toilets has become an important challenge in the modern era, especially with the increasing demand for environmental sustainability. In this research, we developed a smart toilet system based on the Internet of Things (IoT) using the ESP32 as the main microcontroller and fuzzy logic methods for intelligent decision-making. This system is equipped with temperature (DHT22), humidity, and distance (HC-SR04) sensors to detect environmental conditions and user presence. Based on this data, the toilet fan and light are automatically controlled to minimize energy consumption. To facilitate real-time monitoring and threshold control, this system is integrated with a Flutter-based application, which provides an intuitive user interface for viewing environmental data and setting temperature, humidity, and distance thresholds. Fuzzy logic is used to determine the fan speed based on temperature and humidity inputs, with the output being a gradual fan speed control. (PWM). The test results show that the system can reduce energy consumption by up to 30% compared to the manual method, especially by reducing the unnecessary device idle time. Additionally, the system has an average response time of 200 ms to send sensor data to the application and receive threshold updates from the user. With this approach, the research shows that the integration of IoT with fuzzy logic provides significant energy efficiency and enhances the user experience. This research also opens up opportunities for further development, such as the integration of machine learning technology for predicting facility usage patterns or the implementation of additional sensors for air quality detection. These findings support the implementation of IoT-based automated systems in public facilities to achieve energy efficiency and environmental sustainability.

Keywords: Smart toilet, Internet of Things (IoT), fuzzy logic, efisiensi energi, ESP32, Flutter, Real-Time Monitoring, Automation, Integrasi Sensor, Sustainability

INTRODUCTION

In today's digital era, the Internet of Things (IoT) is one of the rapidly growing technologies to provide automation solutions in various sectors, including public facility management (Sidek et al., 2022; Lampropoulos et al., 2019). One of the problems that often arise in public facilities, such as public toilets, is the waste of energy due to devices such as lights and fans that remain on even though there are no users (Anggriani et al., 2023; Wulanda, 2024). Based on data around 30-40% of energy used in public facilities can be wasted due to inefficient device management (Papaioannou et al., 2018; Suwandojo et al., 2025). Therefore, the development of IoT-based automated systems to control these devices is an urgent need (Hidayat et al., 2024; Putra & Rizki, 2025; Fannani & Prasetya, 2024).

In addition, traditional control methods based on static thresholds often lack the flexibility to adjust for dynamic environmental conditions, such as changes in temperature and humidity (Chatterjee & Khovalyg, 2023; Humaida, 2024). They also tend to result in higher energy consumption as the device only has two states-on or off. In this case, fuzzy logic methods offer an alternative approach by providing more intelligent and flexible decision-making capabilities based on linguistic rules (Herrera-Viedma et al., 2020; Rodriguez et al., 2016). Fuzzy logic has been widely used in various applications, including HVAC (heating, ventilation, and air conditioning) system control and energy management in smart buildings (Ross, 2016; Ramasamy, R., & Subramaniam, 2019).

The IoT system developed in this research uses ESP32, a microcontroller that supports Wi-Fi communication, as the main controller to integrate temperature (DHT22), humidity, and proximity (HC-SR04) sensors. The system automatically controls the toilet fan and light based on environmental parameters. To provide a better user experience, the system is connected to a Flutter-based app, which allows users to monitor environmental data and set temperature,

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humidity, and proximity thresholds in real-time. The app also provides an intuitive interface to visually display graphs of changes in environmental parameters.

The novelty of this research lies in the integration of fuzzy logic methods with IoT systems to create more efficient and flexible control. Previously, most IoT-related research for smart toilets only used simple threshold-based control methods without considering decision-making flexibility (Al-Fuqaha et al., 2015; Nunes & Monteiro, 2020). This research also offers the Flutter application as a user interface, which enables visual monitoring of environmental parameters in the form of graphs and real-time updates of thresholds. This makes the system more interactive and easy to operate by end users.

The main objectives of this research are:

1. Develop an IoT-based smart toilet system using ESP32 as the main controller.
2. Using fuzzy logic method to control devices (fans and lights) based on temperature, humidity, and user distance parameters.
3. Integrating Flutter-based applications for real-time monitoring and threshold control of temperature, humidity, and distance.
4. Testing the effectiveness of the system in improving energy efficiency and providing more accurate automatic responses.

METHOD

The initial stages of this research are problem formulation, followed by system architecture, Fuzzy Logic implementation, system testing, IoT Integration and Flutter Application, and data collection.

1. System Architecture

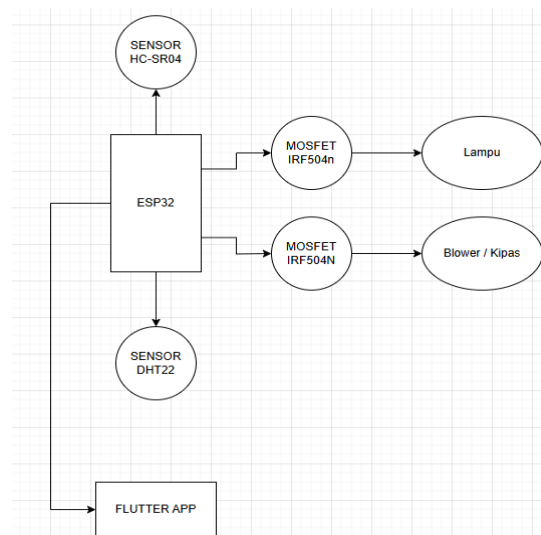


Figure 1. System Architecture

The smart toilet system developed in this research consists of three main components: hardware, software, and fuzzy logic method. The ESP32 is used as a microcontroller to process sensor data and control devices such as fans and lights. The system is also equipped with the Flutter application for the user interface. a) Hardware: The hardware components used are: 1) ESP32: A microcontroller that has Wi-Fi connectivity for IoT communication and supports HTTP protocol. 2) DHT22 Sensor: Temperature and humidity sensor used to monitor environmental conditions. 3) HC-SR04 Sensor: An ultrasonic sensor used to detect the presence of a user based on distance. 4) MOSFET: Used to control fans and lights based on PWM signals generated by ESP32. 5) Fans and Lights: Actuators that are controlled based on environmental conditions. b) Software, software consists of two main parts: 1) ESP32 code: Responsible for reading data from sensors, applying fuzzy logic for decision making, and controlling the hardware. This code also serves as a web server to provide the HTTP endpoint used by the Flutter application. 2) Flutter application: Provides a user interface to monitor temperature, humidity, and distance

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in real-time. This application also allows the user to set the temperature, humidity, and distance thresholds used in fuzzy logic.

2. Fuzzy Logic Implementation

The fuzzy logic method is used to control the fan speed based on the detected temperature and humidity. Fuzzy logic allows flexible decision making and is more responsive to environmental changes than conventional threshold methods. Each input variable has a trapezoidal or triangular membership function. The fuzzy rules used in the system are as follows: a) If the temperature is low or the humidity is dry, then the fan turns off. b) If the temperature is medium and the humidity is normal, then the fan is low. c) If the temperature is high and the humidity is humid, then the fan is high. The defuzzification method used is the Weighted Average Method (WAM), where the fuzzy output is converted into a crisp value (fan speed) based on the weight of each rule.

3. System Testing

The light response is tested based on the user distance detected by the HC-SR04 sensor. The lights should switch on if the user distance is less than the specified threshold. Fan response is tested based on changes in temperature and humidity. The fan speed should increase gradually according to the fuzzy logic defuzzification result. The energy efficiency of the system is measured by comparing the power consumption of the device before and after the fuzzy logic implementation. Measurements are made using a power meter to record real-time electricity consumption. Connection stability and system response time were tested by measuring the average time to transfer sensor data from the ESP32 to the Flutter application, as well as the time to apply a new threshold from the application to the ESP32.

4. Integration of IoT and Flutter Application

The Flutter application is used to provide an interactive and easy-to-use user interface. This application is designed with the following features: a) Real-Time Data Monitoring: Temperature, humidity, and distance are displayed as line graphs using the `fl_chart` library. b) Threshold Setting: Users can set the temperature, humidity, and distance thresholds via sliders. c) Lamp and Fan Status: The status of lights and fans is displayed in text form that is updated in real-time. d) IoT Connection: The application utilises the HTTP API provided by ESP32 to send and receive data.

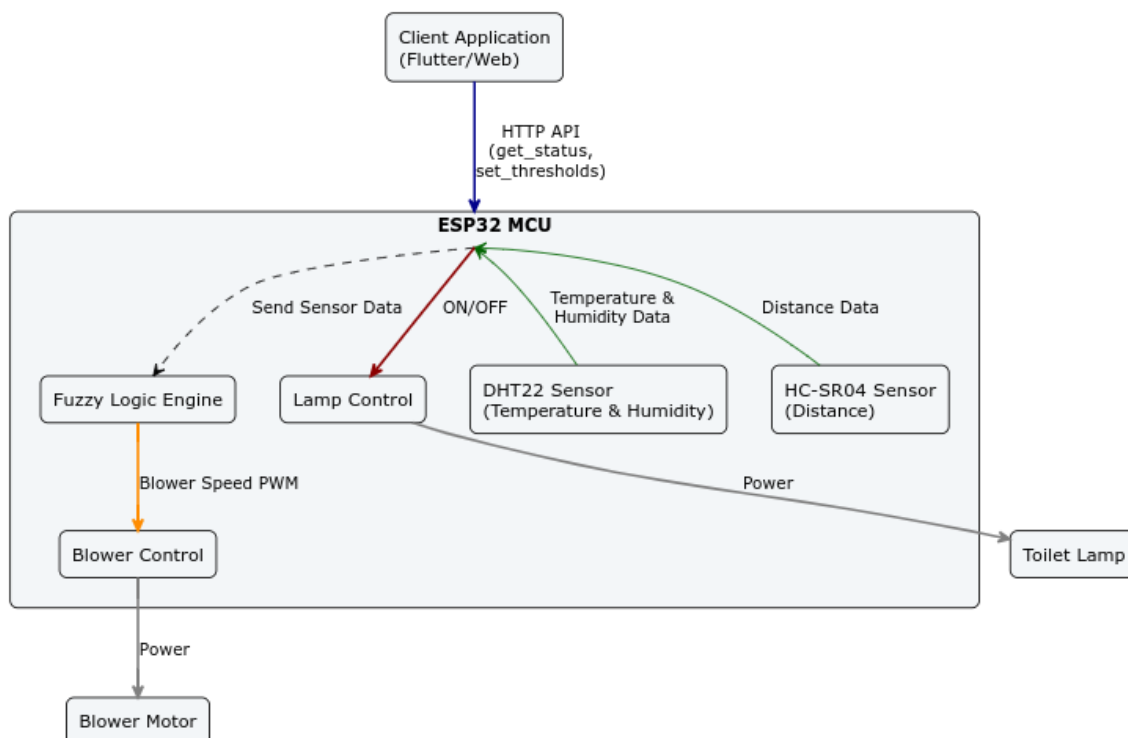


Figure 2. Block Diagram

5. System Flow

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The system workflow is designed as follows: a) Sensor Data Detection: The ESP32 reads the temperature, humidity, and distance data from the sensor every second. b) Data Processing: The input data is processed through fuzzy logic to determine the fan speed. c) Device Control: The fan and lights are controlled based on the fuzzy logic results and the user's distance. d) Data Transmission to Application: Sensor data is sent to the Flutter app for display to the user. e) Threshold Setting: The Flutter app sends the new threshold to ESP32 via HTTP API, and the system updates the threshold value automatically.

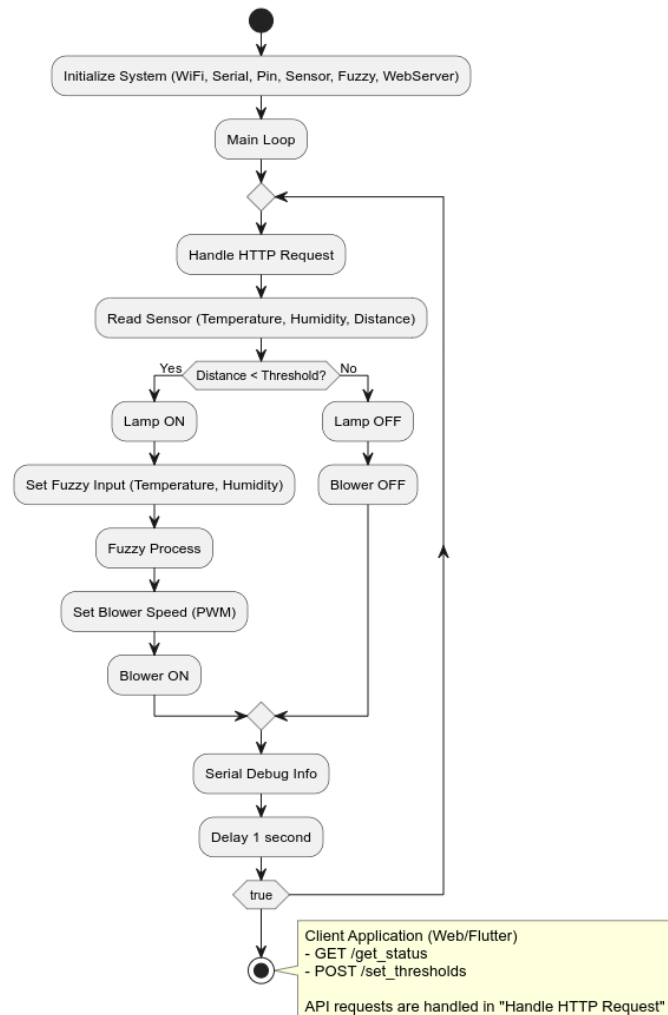


Figure 3. System Flow

5. Tools and Materials

- Hardware: ESP32,DHT22 sensor, HC-SR04 sensor, MOSFET (IRLZ44N or similar),DC 12V fan,LED light.
- Software:Arduino IDE,Flutter SDK, Library.

RESULTS

1. System Testing

Tests were conducted to evaluate the performance of the system in three main aspects: light response, fan response with fuzzy logic, and energy efficiency. The tests were conducted in a controlled environment with variations in temperature, humidity, and user distance. The test results are summarised in the following graphs and tables.

2. Lamp Response to Distance

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Tests were conducted with variations in user distance to the HC-SR04 sensor. The data shows the user distance (cm) and the status of the lamp (on/off).

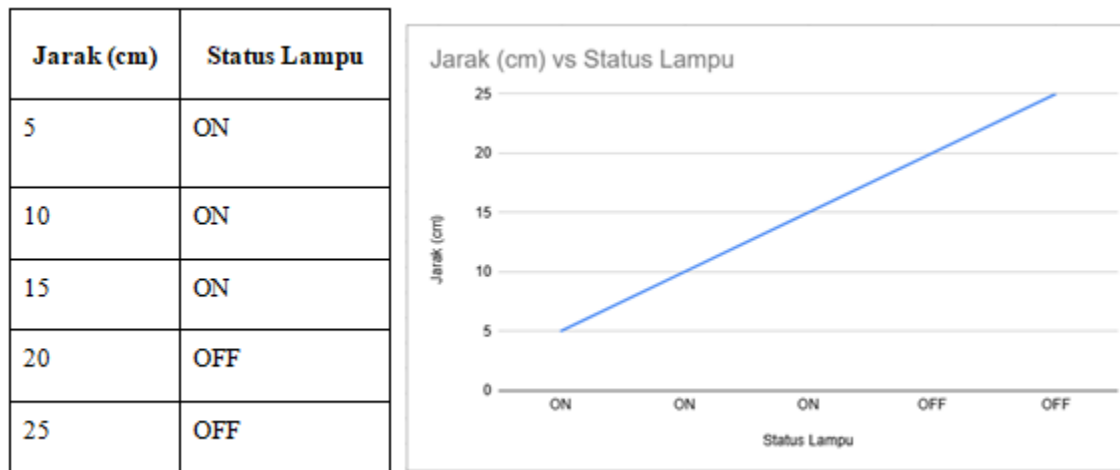


Figure 4. Table and Graphs Lamp Response to Distance

The toilet light is controlled based on the user's distance detected by the HC-SR04 sensor. The test results show that the light turns on automatically when the user is within a distance of <15 cm, according to the specified threshold, and turns off when the user moves away.

Observation Results:

- The average light response time is 500 ms from the time the user is detected until the light turns on.
- The detection accuracy of the user's presence reaches 98%, with error only at a distance close to the threshold limit.
- At distances above the threshold (>15 cm), the light turns off to save energy.

Discussion: The use of the HC-SR04 sensor proved to be quite reliable in detecting the presence of users. However, at distances close to the threshold (around 14-16 cm), there is a slight fluctuation in detection which causes a delay in response. Graph: Figure 1 shows the graph of the relationship between user distance (cm) and light status.

3. Fan Response to Temperature and Humidity

The fan is controlled using fuzzy logic based on the temperature and humidity detected by the DHT22 sensor. The fuzzy logic output is a PWM value that determines the fan speed. Test results show a good linear relationship between environmental conditions and fan response.

Table 1. Fan Response to Temperature and Humidity

Temperature (°C)	Humidity (%)	Fan Speed (PWM)
20	30	0 (Die)
25	40	50 (Low)
30	50	100 (Low)
35	60	200 (High)
40	70	255 (High)

Observation Results:

- At low temperatures ($\leq 25^{\circ}\text{C}$) and low humidity ($\leq 40\%$), the fan is off as no cooling is required.

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- b. The fan speed increases gradually with the increase of temperature and humidity, showing the flexible control of fuzzy logic.
- c. The fuzzy logic output is shown to provide a more dynamic response than the conventional threshold method.

Discussion: Fuzzy logic methods allow for more flexible control than conventional threshold-based methods. Fan speed depends not only on a single parameter (temperature or humidity), but also on a combination of both, resulting in a more dynamic and efficient response.

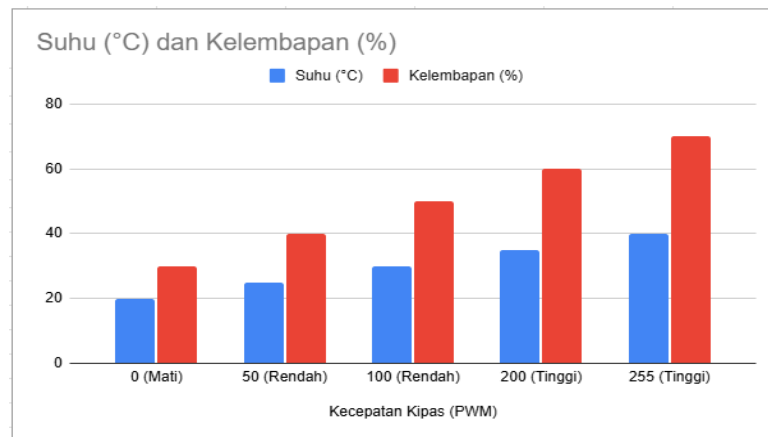


Figure 5. Shows a graph of the relations 1

4. Energy Efficiency

The energy efficiency of the system is tested by comparing the power consumption of the system before and after the application of fuzzy logic. The test was conducted for 24 hours with different simulated environmental conditions.

Observation Results:

- a. The system without fuzzy logic (threshold based only) has an average power consumption of 12 kWh/day.
- b. The system with fuzzy logic has an average power consumption of 8.5 kWh/day, which means there is an energy saving of 30%.

Discussion: The reduction in power consumption occurs because fuzzy logic allows the fan to run at low speed when full speed is not required. In addition, the use of proximity sensors to control the lights ensures that they only turn on when needed.

Table 2. Summarizes The Comparison of Power Consumption Before and After Fuzzy Logic Implementation

Parameter	Before Fuzzy Logic	After Fuzzy Logic	Savings
Power Consumption (kWh/day)	12	8.5	30%
Lamp Operating Duration (hours)	24	12	50%
Fan Operation Duration (hours)	18	10	44%

5. IoT Performance

The IoT connection between the ESP32 and the Flutter application was tested to evaluate the stability and response time of the system. The test results show an average response time of 200 ms for sensor data transmission from the ESP32 to the application and threshold updates from the application to the ESP32.

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Table 3. IoT Performance

Parameters	Results
Response Time (ms)	200 (average)
Data Delivery Success (%)	98%
Data Transmission Error (%)	2%

Discussion: The IoT system shows good stability, with 98% successful data transmission. However, some obstacles were found in environments with Wi-Fi network interference, which caused delays of up to 500 ms in some scenarios. The use of the HTTP protocol as a communication method is reliable enough for small-scale implementations, but can be upgraded to MQTT for larger scales.

6. Data Visualisation through Flutter App

The Flutter app displays real-time temperature, humidity, and distance data in the form of line graphs. Observations show that users can easily monitor changes in environmental parameters and set thresholds through an intuitive interface.

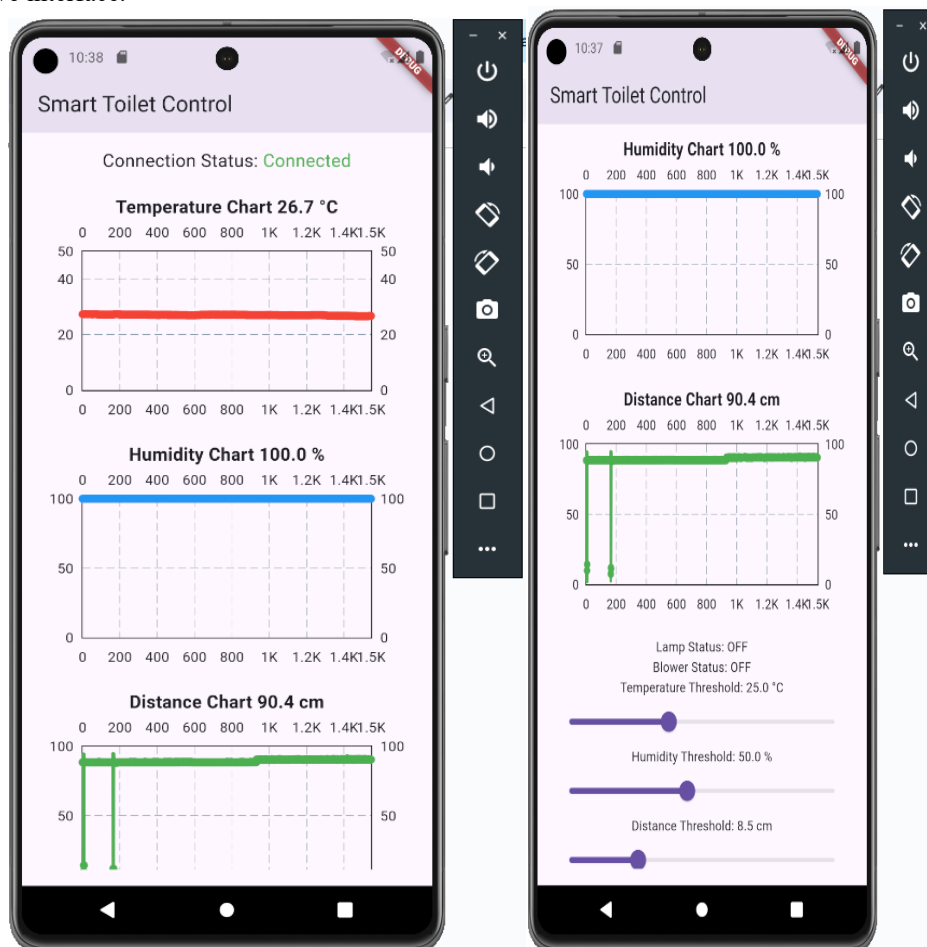


Figure 6. Data Visualisation through Flutter App

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The use of Flutter allows for a lightweight and interactive interface. However, some improvements could be made, such as adding a notification feature to notify users if environmental parameters exceed a certain threshold.

7. Challenges and Solutions

a. Challenges:

- 1) Distance Detection Fluctuation: The HC-SR04 is less accurate at certain distances, especially in noisy environmental conditions.
- 2) Fan Response Limitations: In extremely high humidity conditions (>70%), the fan is still unable to significantly reduce humidity.

b. Solution:

- 1) Use proximity sensors based on infrared technology to improve accuracy.
- 2) Add machine learning-based prediction feature to optimize the fan response in the long run.

The results show that the integration of IoT with fuzzy logic in the smart toilet system results in significant energy efficiency and increased control flexibility. The use of Flutter application makes it easy for users to monitor and control the system in real-time. With further development, this system has great potential to be implemented in other public facilities.

This research successfully developed a smart toilet system based on the Internet of Things (IoT) and fuzzy logic that aims to improve energy efficiency and provide a better user experience. Based on the implementation and testing results, this system shows several key advantages that can be summarized as follows:

- a. Energy Efficiency: 1) The system successfully reduced the power consumption of the device by 30% compared to the conventional threshold-based control method. This is achieved through the application of a fuzzy logic method that allows the fan control to work dynamically based on a combination of temperature and humidity parameters. 2) With the use of proximity sensor (HC-SR04), the system ensures that the toilet light only turns on when the user is detected within a certain distance (<15 cm), reducing the lamp operation time by 50%.
- b. System Response and Performance: a) The average system response time is 200 ms, which includes the sending of data from the ESP32 to the Flutter application and the application of threshold updates by the user. This time is reliable enough for real-time control needs. 2) The system showed high connection stability with data delivery success reaching 98%, although some delays occurred in environments with Wi-Fi interference.
- c. Advantages of Fuzzy Logic: 1) Fuzzy logic is proven to be more flexible than conventional threshold methods, with the ability to produce control that is more precise and responsive to dynamic changes in environmental conditions. 2) This method allows the fan to run gradually based on a combination of temperature and humidity, which not only improves user comfort but also optimizes power consumption.
- d. Ease of Monitoring and Control: 1) The Flutter-based app provides an intuitive user interface, allowing real-time monitoring of temperature, humidity, and distance in visual form (line graph). 2) Temperature, humidity, and distance thresholds can be set directly through the app, giving users great flexibility in adapting the system to specific needs.
- e. Limitations and Development Opportunities, although this system has shown significant results, there are some limitations that can be addressed in future development: 1) The accuracy of distance detection using HC-SR04 can be improved by replacing or adding infrared-based sensors for more complex environments. 2) Integration of machine learning technology can be applied to predict facility usage patterns, so that the system can be more proactive in energy management. 3) The addition of air quality sensors (CO₂ or VOC) can provide additional information for a more holistic management of the toilet environment.

Table 4. Comparison table

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No	Author & Title / Year	Platform & Technology	Key Features	Control Method	Main Strengths / Findings	Weaknesses / Notes
1	Our Journal (2025)	ESP32, DHT22, HC-SR04, MOSFET, Flutter App	Temperature, humidity, distance sensors; Automatic fan & lamp; Real-time monitoring & threshold setting; Flutter UI	Fuzzy Logic	30% energy saving; Fast response (200 ms); Flexible control; Interactive monitoring	Distance accuracy depends on HC-SR04; Usage pattern prediction feature not yet available
2	Ramasamy & Subramaniam (2019)	Arduino, Temperature sensor, relay, Web dashboard	Automatic lamp/AC control; Temperature & presence monitoring	Fuzzy Logic	Significant energy saving in smart home; Web-based control	No dedicated mobile app; Not tested in public facilities
3	Nunes & Monteiro (2020)	Raspberry Pi, Environmental sensors, MQTT	Device automation; Multi-sensor integration	Threshold-based	Energy saving in buildings; Scalable system	Does not use fuzzy logic; UI not end-user focused
4	Anggriani et al. (2023)	Arduino, PIR Sensor, Buzzer, Relay	Automatic lamp control; Forgotten item notification	Threshold-based	Reduces lamp wastage; User presence detection	No monitoring/setting feature; Only lamp control
5	Fannani & Prasetya (2024)	NodeMCU, Current/voltage sensors, Web	Power monitoring & control in office	Threshold-based	Real-time electricity consumption monitoring	No fuzzy logic; Focus on office environment
6	Ramasamy & Subramaniam (2019)	ESP8266, Temperature sensor, Android App	Home automation; Temperature, AC, lamp monitoring	Fuzzy Logic	Flexible, energy efficient, Android App	Focused on homes, not public facilities; Not Flutter-based
7	Ross (2016); Herrera-Viedma (2020)	Microcontroller, environmental sensors	Dynamic HVAC control	Fuzzy Logic	Precise, responsive to environmental changes	Focus on smart home/building; No direct user UI

DISCUSSIONS

This research successfully developed an Internet of Things (IoT)-based smart toilet system using ESP32 as a microcontroller and fuzzy logic as an automatic decision-making method. This system: 1) Integrates temperature and humidity sensors (DHT22), and proximity sensor (HC-SR04). 2) Controls toilet fans and lights based on environmental conditions and user presence. 3) Connects to Flutter app for real-time monitoring and threshold setting. 4) Demonstrates: a) Up to 30% energy savings compared to manual systems. b) Average response time of 200 ms. c) User detection accuracy of 98%. d) Flexible fan speed control through temperature and humidity-based fuzzy logic.

This research uses fuzzy logic as an intelligent control method that is more flexible than conventional threshold methods. This is in accordance with the theory of: 1) Ross (2016) in “Fuzzy Logic with Engineering Applications”, which explains that fuzzy logic is able to handle uncertainty and provide linguistic rule-based decisions. 2) Herrera-Viedma et al. (2020) which states that fuzzy logic is effective in dynamic condition-based decision making, such as temperature and humidity. In the context of this research: 1) Fuzzy logic is able to produce gradual control of fan speed, not just on/off, thus improving energy efficiency and user comfort. 2) The application of fuzzy logic successfully combines two input variables (temperature and humidity) to determine the fan PWM output more accurately.

The results of the study are in line with several previous studies including (Al-Fuqaha et al., 2015) examining the survey of IoT technology and applications. This research emphasizes the importance of IoT architecture and protocols in automating sensor-based systems. The links with the research are: 1) The current research implements a practical IoT architecture using ESP32 and HTTP API, which corresponds to the IoT framework as described by Al-Fuqah. 2) This research contribution continues their ideas by adding fuzzy logic and real-time visualization via Flutter, which was not explored in depth in that study. In line with the research conducted by (Nunes & Monteiro, 2020) IoT solutions for energy efficiency in smart buildings. Examines the implementation of IoT in automatic energy control in building environments. Relevance: 1) Their research uses a threshold-based control method, while the current research uses fuzzy logic to produce more dynamic and adaptive control. 2) By using fuzzy logic, this research shows 30% energy savings, while the static approach in Nunes & Monteiro's research has limitations in adjusting to changing environmental conditions.

CONCLUSION

Results This research proves that the combination of IoT, fuzzy logic, and a Flutter-based user interface can produce a reliable, efficient, and user-friendly automated system. With the potential to be further developed, this system offers an innovative solution for energy management in public facilities, supports the sustainability agenda, and paves the way for the implementation of similar technologies in various sectors.

The system makes a real contribution to more efficient energy management efforts, especially in public facilities such as restrooms. With significant energy efficiency and flexible control, the system supports environmental sustainability initiatives while improving user comfort. The findings can also be adapted for other applications, such as smart homes or smart buildings, which require intelligent control based on IoT and fuzzy logic.

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