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An Advanced Intelligent Monitoring and Controlling System of Wastewater Aerators using Fuzzy Logic Based on Internet of Things (IoT)

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Abstract: Wastewater treatment represents a major environmental and industrial challenge due to the need for sustainable pollutant removal and efficient resource management. The aeration machine plays a crucial role in maintaining sufficient dissolved oxygen for microbial degradation, yet its conventional manual operation typically around 11 hours per dayleads to inefficiencies and inconsistent process performance. This research proposes the design and development of an intelligent fuzzy logic–based control system integrated with the Internet of Things (IoT) to enhance the operational efficiency of wastewater aeration. The fuzzy logic controller (FLC) enables real-time adaptive decision-making to handle nonlinear and uncertain wastewater dynamics, while IoT provides continuous monitoring and remote control capabilities. Experimental results demonstrate that the proposed system optimizes aerator run time, reduces power consumption, maintains stable chemical oxygen demand (COD) and biological oxygen demand (BOD) levels, and improves effluent quality compared to manual operation. The integration of fuzzy logic and IoT contributes toward smart and sustainable wastewater treatment operations.
Keywords: Fuzzy logic, Internet of Things, Wastewater aeration, Intelligent control, Energy efficiency, Environmental sustainability.

1. Introduction

Wastewater management is one of the most critical aspects of industrial and environmental sustainability. Efficient treatment of wastewater not only ensures compliance with environmental regulations but also reduces energy consumption and operational costs. The aeration subsystem, which maintains adequate chemical oxygen demand (COD) and biological oxygen demand (BOD) levels for microbial degradation, often consumes more than 50% of the total energy in wastewater treatment plants [1]. Conventionally, aerators are operated manually or on fixed schedulestypically 11 hours per dayresulting in excessive energy usage during low-load conditions and insufficient aeration during peak loads.

To achieve optimization, an intelligent control system capable of adapting to changing wastewater characteristics is required. Fuzzy logic control (FLC) has proven to be an effective method for managing uncertain and nonlinear processes such as wastewater treatment [2],[3]. Unlike conventional proportional–integral–derivative (PID) controllers, fuzzy logic controllers rely on human-like reasoning, which allows flexible decision-making under uncertainty [4].

Meanwhile, the Internet of Things (IoT) has emerged as a powerful technology enabling remote connectivity, real-time monitoring, and cloud-based data analytics in industrial processes[5],[6]. The combination of fuzzy logic and IoT can provide a robust, adaptive, and remotely controllable aeration system, improving both energy efficiency and environmental outcomes.

The objective of this study is to design and implement an intelligent control system for wastewater aerators using a fuzzy logic approach integrated with IoT. The proposed system monitors key process parameters such as COD through IoT sensors, while the fuzzy logic algorithm dynamically controls aerator operation to maintain optimal oxygenation and reduce energy consumption.

2. Methodology

2.1 System architecture

The proposed system consists of three major subsystems:

a. **IoT Sensor Network** – Collects data COD and BODsensors using a microcontroller (ESP32) with Wi-Fi connectivity.
b. **Fuzzy Logic Controller (FLC)** – Determines aerator operation mode (ON/OFF) based on real-time sensor inputs.

c. **Cloud and User Interface –** Utilizes an IoT Thing Speak platform for remote data visualization and control.

2.2 Fuzzy logic design

The FLC uses two primary input COD and BOD concentration levels with Gauss membership functions defined for three linguistic variables: Low (L), Medium (M), and High (H), as shown in Fig.1 and Fig.2

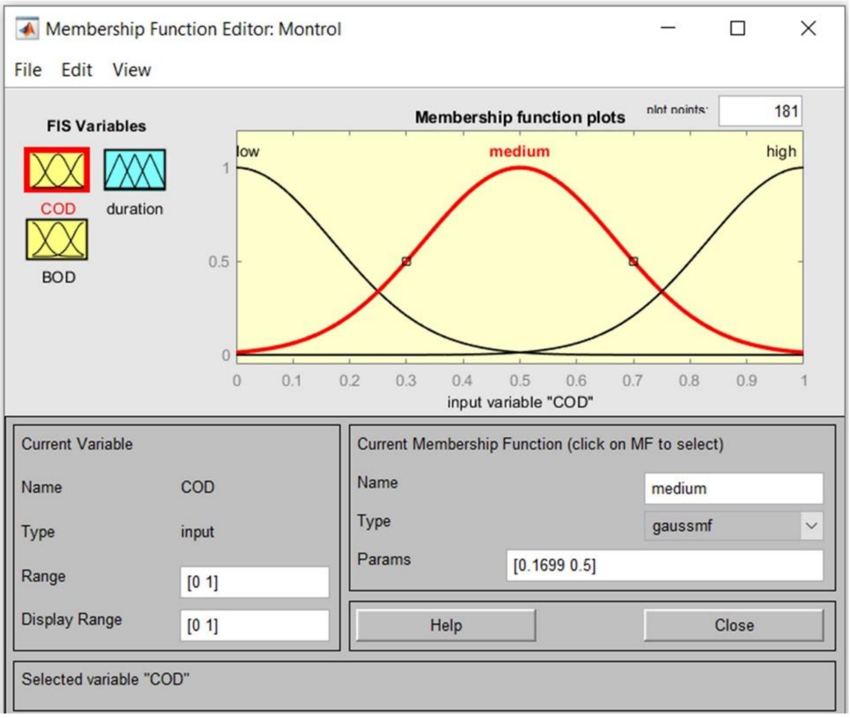

Figure 1: Input variables COD

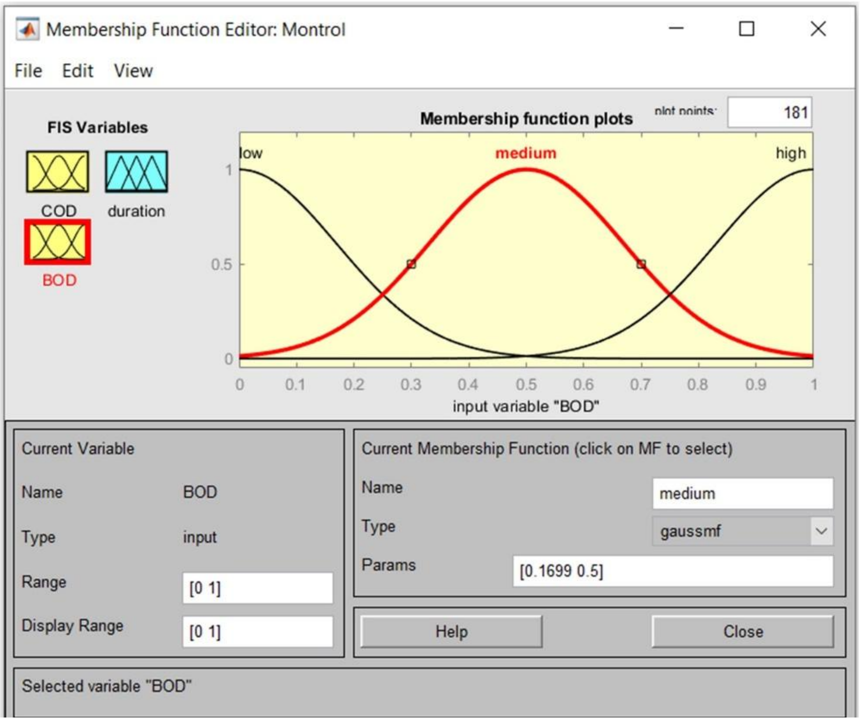

Figure 2:. Input variables BOD

The output duration aerator level by Gauss membership functions is defined by three linguistic variables: Short (S), Average (A), and Long (L) corresponding to the operating aerator machine, shown in Fig. 3.

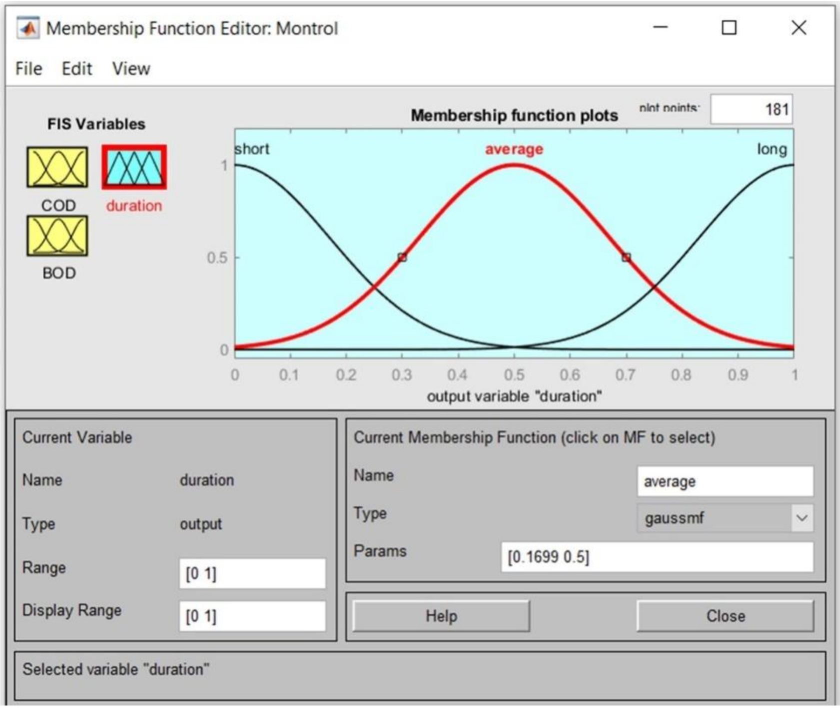

Figure 3: Output duration aerator

Fuzzy rule bases are established to map sensor readings to control decisions, a rule base that defines the relationship between input and output variables, the rule view, and the surface view that defines the mathematical expressions to calculate the output shown in Fig.4 and Fig.5.

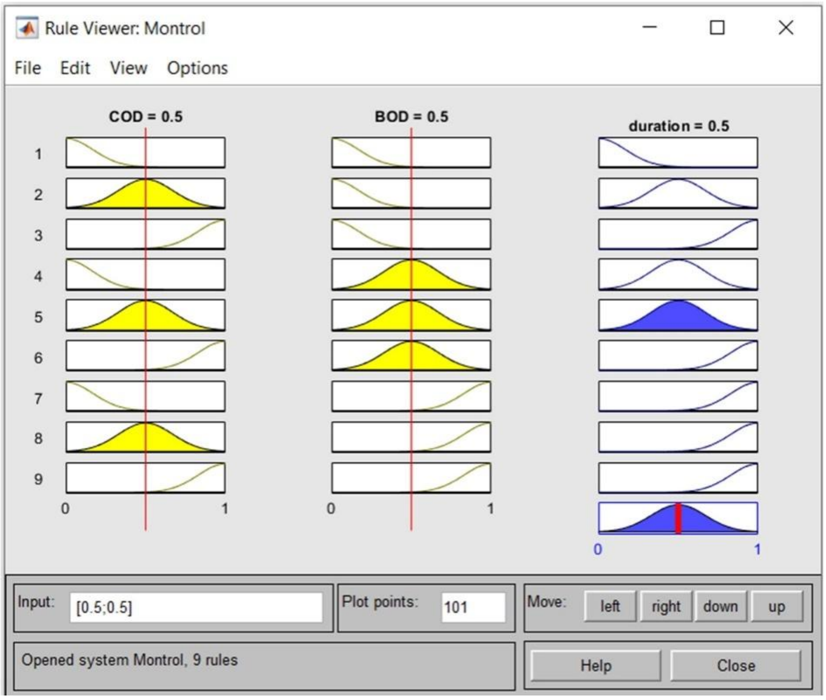

Figure 4: Rule viewer

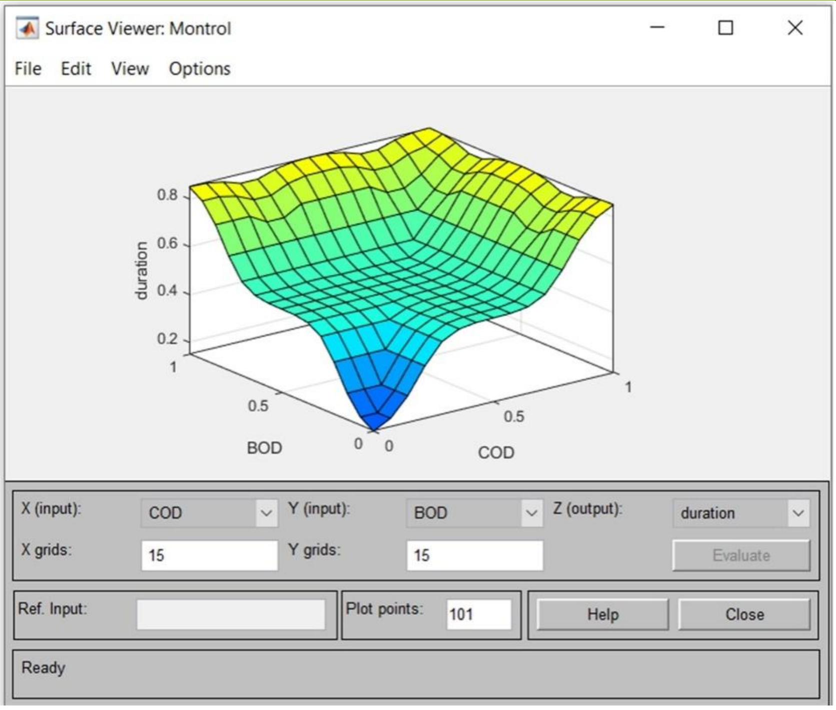

Figure 5: Surface viewer

2.3 IoT implementation

Sensor readings are sent via MQTT protocol to a cloud server. A dashboard displays real-time COD and BOD. Data logs are stored for trend analysis and controller optimization. Alerts are sent to operators when CODand BOD falls below the critical limit. Remote control of aerator operation can also be performed through the web or mobile application.

2.4 Experimental setup

A laboratory-scale aeration tank (capacity = 100 L) was used to validate the system. Temperature and pH sensors provided continuous feedback to the fuzzy controller. Performance was compared between manual operation (fixed 11 h/day) and intelligent fuzzy-IoT control under varying wastewater load conditions.

3. Results and Discussion

3.1 Real-time monitoring and performance evaluation

The present IoT dashboard visualization, which displays real-time data from sensors through an MQTT-based monitoring interface, is shown in Fig. 6. The system automatically triggers aerator activation when the dissolved oxygen level drops below 4 mg/L.

The fuzzy logic control successfully maintained COD and BOD levels within the optimal range (2–4 mg/L) under variable conditions. Compared to the manual baseline:

- **Aerator runtime** decreased by approximately **35–40 %**,
- **Energy consumption** reduced by **30 %**,
- **Effluent COD concentration** decreased by **15 %.**
- **Effluent BOD concentration** decreased by **15 %.**

These improvements confirm that the fuzzy controller provides adaptive, real-time decision-making that compensates for variations in influent load.

3.2 IoT system Performance

The IoT system ensured reliable communication between sensors, the controller, and the cloud platform with an average data latency below 2 s. Operators could remotely monitor COD and BOD trends and adjust settings if necessary. This connectivity greatly improves maintenance scheduling and fault detection [7], [8], [9], [10].

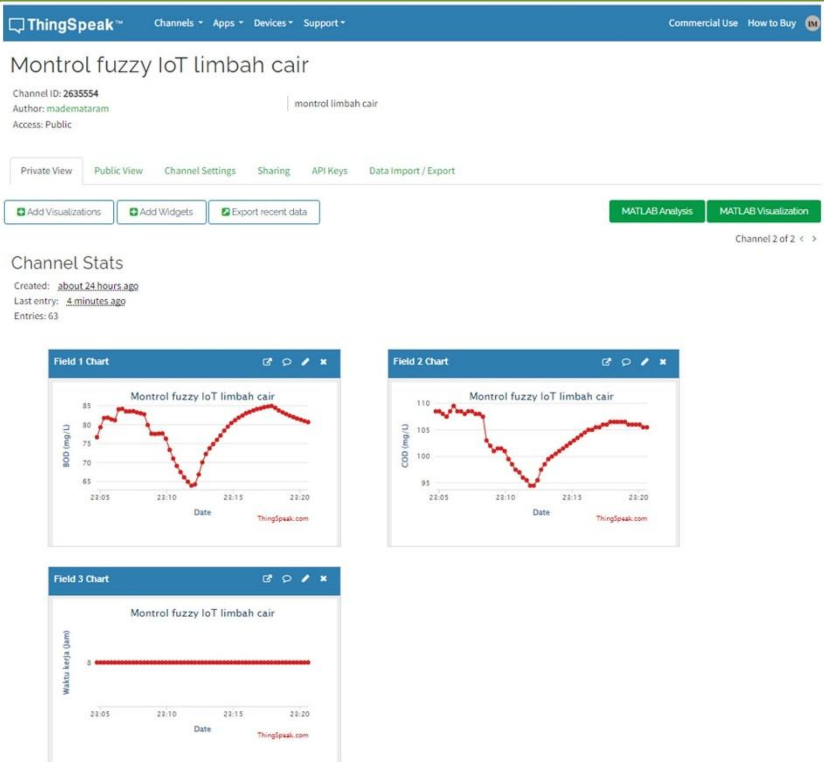

Figure 6: Real-time IoT dashboard visualization during system operation.

3.3 Discussion

The integration of FLC and IoT provides several advantages:

1. **Adaptability:** Fuzzy logic can handle nonlinear, time-varying characteristics of wastewater better than fixed or PID controllers [11],[12].
2. **Energy Efficiency:** The system dynamically reduces aerator usage when DO levels are sufficient, minimizing wasted energy [13],[14].
3. **Scalability:** IoT enables deployment across multiple aerators with centralized monitoring.
4. **Sustainability:** Reduced energy use and improved effluent quality contribute to lower carbon footprint and better compliance with environmental standards.

However, challenges include sensor calibration drift, network reliability, and security of IoT data transmission. Future improvements may include predictive control based on AI models such as ANFIS or deep learning [15],[16].

4. Conclusion

This paper presented the design and implementation of an intelligent control system for wastewater aeration using a fuzzy logic method integrated with the Internet of Things. The system was able to maintain optimal COD and BOD levels, reduce aerator runtime and energy consumption, and provide remote monitoring capabilities. The fuzzy logic approach effectively managed system uncertainty, while IoT integration enabled real-time visibility and control. This hybrid approach is promising for sustainable and energy-efficient wastewater treatment operations. Future research will focus on large-scale deployment, multi-parameter optimization, and AI-based predictive maintenance.

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