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Research Article

Development of a Multi-Sensor Fuzzy Logic-Based Automatic Water Gate Control System for Real-Time Biodiesel Oil Leak Monitoring

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Abstract

The rapid growth of the biodiesel industry has contributed to economic development but has also increased the risk of environmental pollution caused by oil-contaminated industrial wastewater. Conventional wastewater control systems generally rely on manual monitoring, resulting in delayed detection and ineffective responses to oil leakage incidents. This study aimed to develop a multi-sensor fuzzy logic-based automatic water gate control system for real-time biodiesel oil leak monitoring. The proposed system employed an Arduino Uno microcontroller integrated with a TCS34725 color sensor, a turbidity sensor, and an HC-SR04 ultrasonic sensor to detect oil contamination, water turbidity, and water level, respectively. A Sugeno fuzzy logic algorithm was implemented to process sensor data and automatically control the water gate and pump operation based on predefined decision rules. Experimental results showed that the TCS34725 sensor successfully distinguished water and biodiesel oil, with red (R) values of 44–47 for water and 49–54 for oil. The turbidity sensor generated values ranging from 969–1424 NTU for water and −300 to −2705 NTU for biodiesel oil. The developed system reliably closed the water gate upon oil detection and activated the appropriate pump according to water level conditions. These findings demonstrate that the proposed intelligent control system provides an effective and reliable solution for real-time biodiesel wastewater monitoring, contributing to improved industrial wastewater management and reduced environmental pollution risks.

Keywords: *Automatic Water Gate Control; Fuzzy Logic; Industrial Wastewater Monitoring; Multi-Sensor Integration; Real-Time Monitoring.*

How to Cite:

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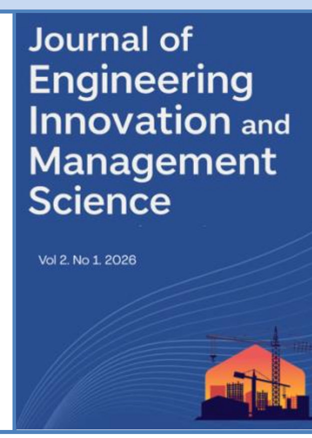

INTRODUCTION

The rapid development of the industrial sector has become one of the primary drivers of economic growth by increasing production capacity, expanding employment opportunities, and supporting the availability of various goods and services required by society. Among these industries, biodiesel production has gained increasing attention because of its contribution to renewable energy development and sustainable economic growth (Klymchuk et al., 2020; Mizik & Gyarmati, 2021; Osman et al., 2023; Suhara et al., 2024). Despite these advantages, industrial expansion has also introduced significant environmental challenges associated with the generation of industrial wastewater. Biodiesel production processes often produce liquid waste containing oil residues that require proper treatment before being discharged into the environment. Inadequate management of oil-contaminated wastewater may lead to severe pollution of rivers, lakes, and coastal waters. Oil contamination can reduce water quality by forming surface films that inhibit oxygen transfer and disturb aquatic ecosystems. The long-term accumulation of oil pollutants may also threaten biodiversity by damaging habitats and reducing the survival of aquatic organisms. Furthermore, environmental degradation caused by industrial wastewater directly affects surrounding communities that depend on clean water resources for domestic, agricultural, and fisheries activities. Consequently, improving wastewater management has become an important priority for industries seeking to achieve both operational efficiency and environmental sustainability. Therefore, the development of intelligent technologies capable of detecting and controlling wastewater contamination is essential for minimizing environmental risks while supporting sustainable industrial operations.

Environmental pollution caused by accidental oil leakage has become an increasingly important concern because such incidents often occur unexpectedly and spread rapidly through industrial drainage systems. Oil leakage can originate from damaged storage facilities, distribution pipelines, or production equipment, allowing contaminants to reach natural water bodies before appropriate mitigation measures are implemented (D. Atoufi & Lampert, 2020; Etim et al., 2026). Once discharged into rivers or coastal areas, oil residues can persist for extended periods and significantly reduce the ecological quality of aquatic environments. Previous environmental incidents have demonstrated that delayed responses to oil leakage may result in extensive ecological damage, including the destruction of aquatic habitats and the decline of fisheries productivity. These environmental impacts are frequently accompanied by substantial economic losses resulting from remediation activities and decreased resource availability. In many industrial facilities, early identification of oil contamination remains challenging because monitoring activities are still dependent on routine visual inspections performed by human operators. Such inspection methods are generally unable to provide continuous observation or immediate responses when leakage occurs. Consequently, contaminated wastewater may continue flowing through drainage channels before corrective actions can be initiated. This condition highlights the necessity for intelligent monitoring systems capable of continuously identifying contamination events and automatically initiating appropriate control actions. Accordingly, integrating advanced sensing technologies into industrial wastewater management has become an important strategy for reducing environmental pollution and improving operational safety.

The implementation of automation technology has transformed industrial monitoring systems by enabling continuous observation, rapid decision-making, and improved operational efficiency. Embedded systems equipped with intelligent sensors provide an effective platform for monitoring environmental parameters under dynamic operating conditions. Various sensing technologies have been developed to measure liquid characteristics, including color, turbidity, and water level, each providing complementary information regarding wastewater conditions (Adjovu et al., 2023; Che et al., 2026; Chen et al., 2023; Zainurin et al., 2022). Nevertheless, many existing monitoring systems rely on a single sensing parameter, limiting their capability to accurately distinguish oil contamination from normal wastewater variations. In addition, wastewater gate operation and pumping processes in many industrial facilities continue to depend on manual intervention, reducing response speed during emergency situations. Manual operation increases the possibility of delayed decision-making, particularly when oil leakage occurs suddenly or in relatively small quantities that are difficult to observe visually. The integration of multiple sensors with intelligent decision-making algorithms offers an opportunity to improve monitoring reliability while reducing dependence on human operators. Fuzzy logic has become one of the most suitable approaches for handling uncertain environmental conditions because it can simultaneously process multiple input variables and generate adaptive control decisions (Dong et al., 2021; Hosseinpour & Martynenko, 2023; Morales Escobar et al., 2020; Tang & Ahmad, 2024). The combination of multi-sensor monitoring and fuzzy logic-based control is therefore expected to improve the effectiveness of automatic wastewater management systems. Such an integrated approach can contribute to safer industrial operations while minimizing the environmental impacts associated with biodiesel wastewater contamination.

Although significant advances have been achieved in intelligent control systems, existing studies have primarily investigated fuzzy logic, multi-sensor integration, industrial wastewater monitoring, and oil leak detection as separate research domains. Previous studies demonstrated that fuzzy logic provides effective decision-making capabilities for intelligent control applications across industrial automation, energy management, and environmental systems, yet these approaches mainly focused on optimizing controller performance without addressing integrated wastewater management applications (Dumitrescu et al., 2021; Ibrahim et al., 2023; Morales Escobar et al., 2020). Similarly, recent developments in multi-sensor integration have substantially improved sensing accuracy, data fusion, and system reliability in navigation, localization, remote sensing, and industrial measurement systems; however, these technologies have rarely been applied to intelligent wastewater control systems that require simultaneous environmental monitoring and automatic operational responses (Cai et al., 2024; Samadzadegan et al., 2025; Zhuang et al., 2023). Furthermore, industrial wastewater monitoring research has increasingly adopted IoT, cloud computing, predictive analytics, and deep learning to improve monitoring performance, but these systems generally emphasize data acquisition, quality assessment, or fault diagnosis rather than intelligent automatic control of wastewater discharge (Chavhan et al., 2025; Hakak et al., 2020; Li et al., 2021; Salem et al., 2022). Likewise, oil leak detection technologies have predominantly been developed for crude oil and gas pipeline infrastructures using wireless sensor networks, IIoT, image processing, and deep learning, with limited attention given to biodiesel wastewater channels requiring immediate control actions after contamination detection (Ahmed et al., 2023; Idachaba & Rabiei, 2021; Spandonidis et al., 2022). Therefore, a significant research gap remains in developing an integrated intelligent system that combines multi-sensor data acquisition, fuzzy logic-based decision-making, and automatic water gate control for real-time biodiesel wastewater management. To address this gap, the present study develops a multi-sensor fuzzy logic-based automatic water gate control system that integrates color, turbidity, and water-level sensing to enable real-time biodiesel oil leak monitoring and autonomous gate and pump operation, thereby providing a more comprehensive and responsive solution for industrial wastewater management.

This study aims to develop a multi-sensor fuzzy logic-based automatic water gate control system for real-time biodiesel oil leak monitoring. The proposed system integrates a TCS34725 color sensor, a turbidity sensor, and an HC-SR04 ultrasonic sensor to obtain complementary information regarding wastewater characteristics and water level conditions. An Arduino Uno microcontroller is employed as the primary embedded platform for sensor integration and automatic control. A Sugeno fuzzy logic algorithm is implemented to process multiple sensor inputs and determine appropriate operational decisions based on predefined rule sets. The developed system is designed to automatically close the water gate when oil contamination is detected and activate the pumping mechanism according to the measured water level. This automation strategy is expected to reduce the dependence on manual monitoring and improve the response speed during oil leakage incidents. In addition, the integration of multiple sensors is intended to enhance detection reliability by combining different physical characteristics of contaminated wastewater. The proposed prototype also aims to demonstrate the feasibility of applying intelligent control technology to biodiesel wastewater management using affordable embedded hardware. The performance of the developed system is evaluated through experimental testing involving sensor validation, fuzzy logic implementation, and integrated system operation. Ultimately, this study seeks to provide an intelligent, reliable, and cost-effective solution for improving industrial wastewater monitoring and supporting environmentally sustainable biodiesel production.

METHODS

Research Design

This study employed an experimental engineering design to develop and evaluate a multi-sensor fuzzy logic-based automatic water gate control system for real-time biodiesel oil leak monitoring. The research adopted a prototype development approach to integrate sensing devices, embedded control hardware, and intelligent decision-making algorithms into a unified monitoring system. The experimental design was intended to evaluate the capability of the developed system to detect biodiesel oil contamination and automatically regulate wastewater discharge under different operating conditions. Three physical parameters, including liquid color, turbidity, and water level, were selected as primary input variables because they represent important characteristics of wastewater contaminated by biodiesel oil. The collected sensor data were processed using a Sugeno fuzzy logic algorithm to generate adaptive control decisions for water gate movement and pump operation. System performance was evaluated through a sequence of laboratory-scale experiments consisting of individual sensor validation, fuzzy logic verification, and integrated prototype testing. The prototype was operated under controlled experimental conditions to minimize environmental disturbances and ensure measurement consistency throughout the testing process. The effectiveness of the proposed system was assessed based on its ability to accurately identify oil contamination and execute automatic control actions according to predefined fuzzy rules. This research framework was designed to demonstrate the applicability of intelligent embedded control technology for industrial wastewater automation while improving operational reliability and environmental protection.

Materials and Equipment

The experimental system was constructed using an Arduino Uno microcontroller as the central processing unit responsible for data acquisition, fuzzy logic computation, and actuator control. A TCS34725 color sensor was utilized to identify variations in RGB values associated with clean water and biodiesel oil contamination. Water turbidity was monitored using a turbidity sensor capable of measuring changes in liquid transparency that occur during contamination events. An HC-SR04 ultrasonic sensor was employed to continuously determine water level conditions within the prototype channel and provide information for pump activation. Automatic gate movement was performed using a DC motor controlled through an L298N motor driver module, while a miniature water pump simulated wastewater transfer during the experimental process. A 20 × 4 liquid crystal display was incorporated to present sensor readings and system operating status in real time. Biodiesel oil and clean water were prepared as testing media to simulate contamination scenarios under laboratory conditions. MATLAB Fuzzy Logic Toolbox was employed to design, simulate, and validate the Sugeno fuzzy inference model before its implementation on the embedded platform. Additional electronic components, including jumper cables, regulated power supplies, connecting wires, and prototype structural materials, were used to assemble the complete automatic monitoring system.

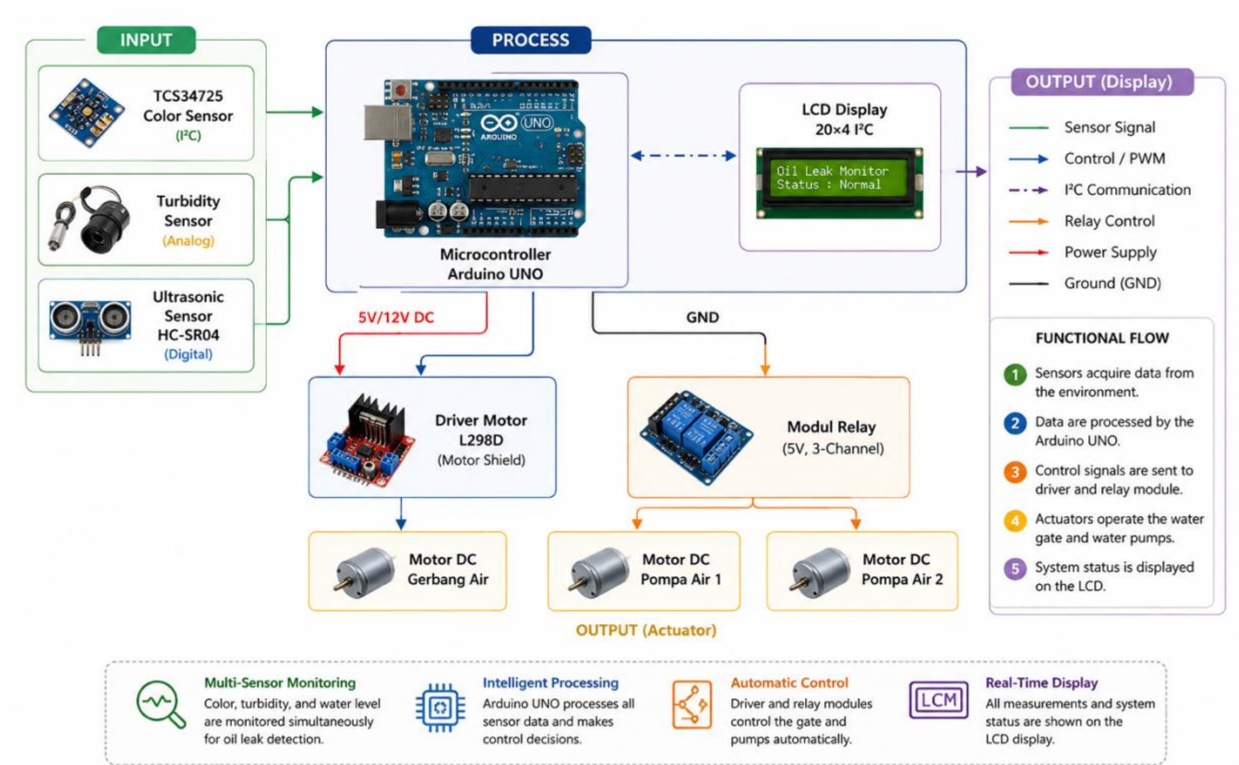

Figure 1. Electronic architecture design of the proposed multi-sensor fuzzy logic-based automatic water gate control system.

Instrumentation and Data Collection

Experimental data were collected through a structured testing procedure consisting of sensor calibration, fuzzy logic validation, and integrated system evaluation. The TCS34725 sensor was initially calibrated by repeatedly measuring RGB values obtained from clean water and biodiesel oil samples to determine representative color characteristics for each medium. Subsequently, the turbidity sensor was evaluated by recording turbidity values under both uncontaminated and contaminated wastewater conditions to assess its capability for distinguishing liquid properties. The HC-SR04 ultrasonic sensor was validated by comparing sensor measurements with manual ruler measurements to determine the accuracy of water level detection. All sensor measurements were repeated under identical experimental conditions to evaluate measurement consistency and operational stability. The validated sensor outputs were then utilized as input variables for the Sugeno fuzzy logic controller. Automatic control decisions generated by the fuzzy inference system included water gate opening or closing and pump activation according to predefined operating rules. Integrated system testing was conducted by introducing biodiesel oil into the prototype channel under various water-level conditions to observe the response of the automatic control mechanism. Sensor outputs and actuator responses were continuously monitored and recorded throughout the experiments. The resulting dataset was subsequently used to evaluate the reliability and effectiveness of the proposed intelligent monitoring system.

Data Analysis

The collected experimental data were analyzed using a descriptive quantitative approach to evaluate sensor performance and the effectiveness of the proposed intelligent control system. Sensor responses were first examined by comparing measurements obtained from clean water and biodiesel oil samples to determine their capability for distinguishing contamination conditions. RGB values generated by the TCS34725 sensor were analyzed to identify characteristic color differences, while turbidity measurements were evaluated to determine changes in wastewater transparency caused by oil contamination. Water-level measurements obtained from the HC-SR04 ultrasonic sensor were compared with manual measurements to assess sensor accuracy. Following sensor validation, all input variables were processed using the Sugeno fuzzy logic algorithm through the stages of fuzzification, rule-based inference, and defuzzification. The resulting fuzzy outputs determined the operational status of the automatic water gate and pumping system according to predefined decision rules. System effectiveness was evaluated by comparing expected operational responses with the actual behavior of the developed prototype under different contamination scenarios. Finally, the experimental findings were interpreted to determine the feasibility, reliability, and practical applicability of the proposed multi-sensor fuzzy logic system for real-time biodiesel wastewater monitoring.

Experimental Procedure

The experimental procedure consisted of five sequential stages designed to ensure systematic prototype development and performance evaluation. The first stage involved designing and assembling the hardware prototype by integrating the Arduino Uno microcontroller, sensing devices, actuator components, and display module into a single embedded control system. The second stage focused on sensor calibration to establish the operating ranges and response characteristics of the TCS34725 color sensor, turbidity sensor, and HC-SR04 ultrasonic sensor under clean water and biodiesel oil conditions. The third stage involved developing the Sugeno fuzzy logic controller by defining input membership functions, constructing fuzzy rules, validating the inference model using MATLAB Fuzzy Logic Toolbox, and implementing the validated algorithm into the Arduino platform. The fourth stage comprised individual subsystem testing to verify communication among sensors, actuators, and the embedded controller while ensuring that each component operated according to the designed specifications. The final stage consisted of integrated prototype testing by introducing biodiesel oil into the wastewater channel under different water-level conditions to simulate contamination events. During this stage, sensor data were continuously processed by the fuzzy logic controller to generate automatic decisions regarding water gate movement and pump activation. The operational responses of the developed system were observed and recorded for every testing scenario. Finally, the experimental results were analyzed to evaluate system responsiveness, operational stability, and the overall capability of the proposed prototype to support intelligent industrial wastewater management.

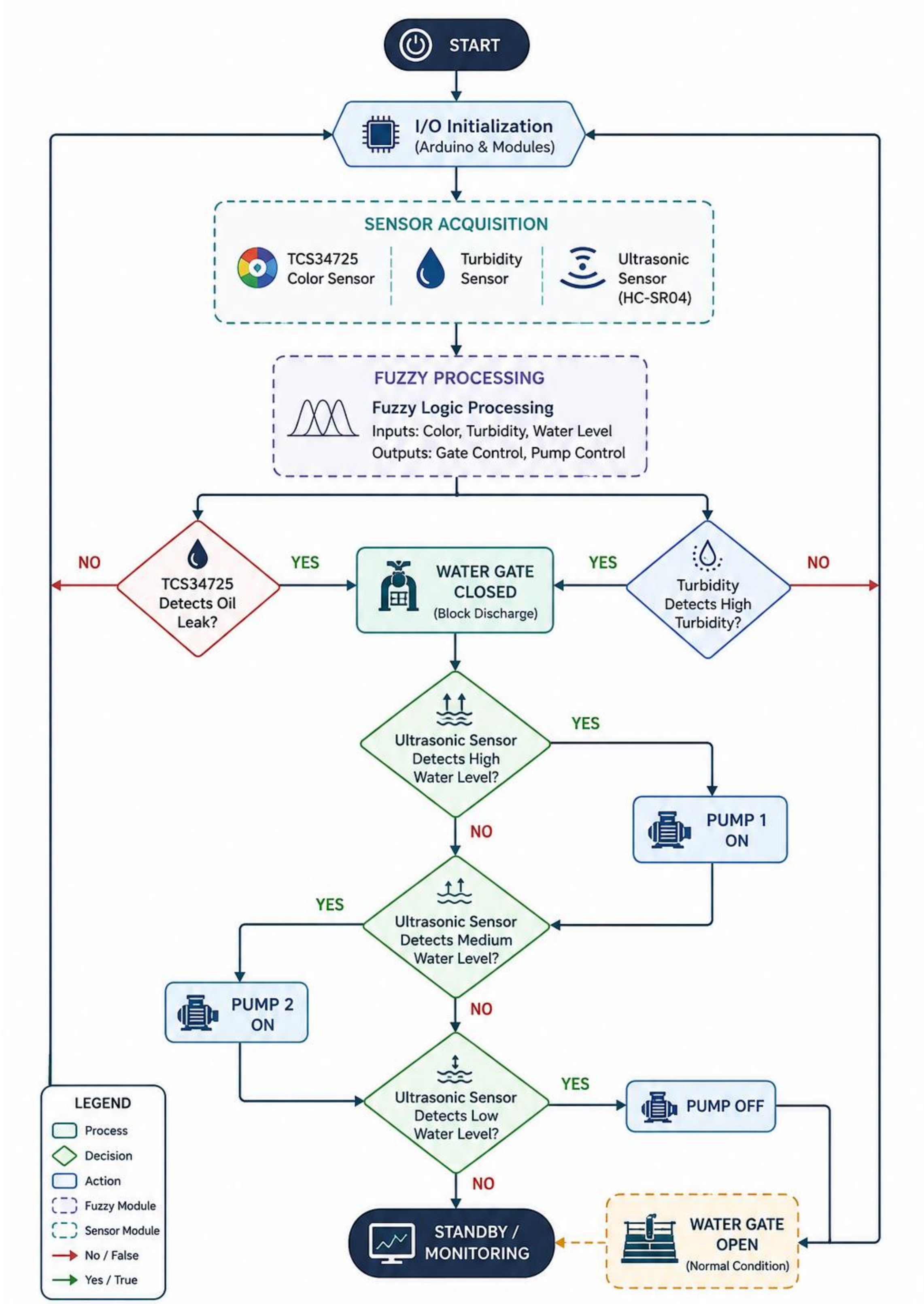

Figure 2. Research Method Flow

RESULT AND DISCUSSIONS

ontrolled using the Sugeno fuzzy logic method. The prototype configuration is presented in Figure 3, the circuit scheme is shown in Figure 4, and the Sugeno fuzzy logic interface is shown in Figure 5.

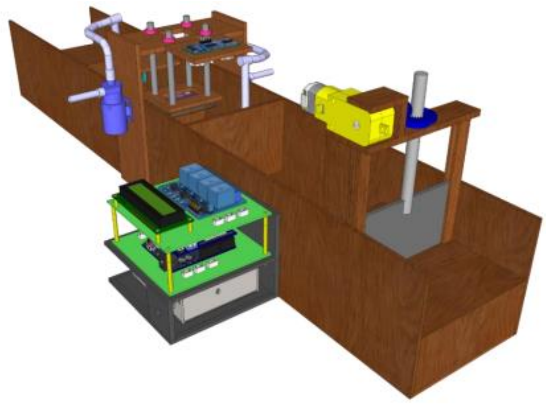

Figure 3. Prototype design of the industrial irrigation system.

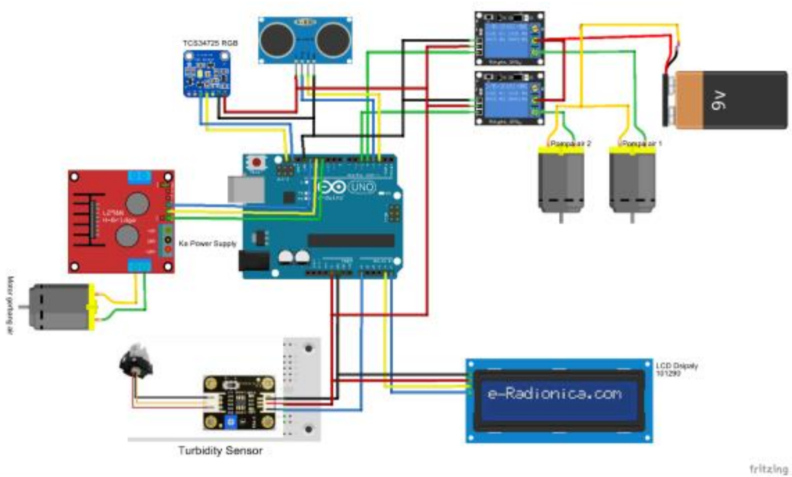

Figure 4. Circuit scheme of the proposed automatic water gate control system.

Figure 5. Sugeno fuzzy logic interface used in the control system.

TCS34725 Color Sensor Testing

The TCS34725 color sensor was tested to evaluate its ability to distinguish water and biodiesel oil based on RGB values. The test results showed that the sensor produced different red-channel values for water and oil. In water conditions, the red value ranged from 44 to 47, whereas in oil conditions, the red value ranged from 49 to 54. This difference indicates that the TCS34725 sensor can be used as an initial detection input for identifying oil contamination in the wastewater channel. Repeated measurements also showed stable RGB readings, particularly under static water conditions. The test results are presented in Table 1 and visualized in Figure 6.

Table 1. TCS34725 color sensor testing results.

Data	Sensor TCS34725 1 R	Sensor TCS34725 1 G	Sensor TCS34725 1 B	Sensor TCS34725 2 R	Sensor TCS34725 2 G	Sensor TCS34725 2 B	Sensor TCS34725 3 R	Sensor TCS34725 3 G	Sensor TCS34725 3 B
1	46	97	88	46	97	88	46	97	88
2	46	97	88	46	97	88	46	97	88
3	46	97	88	46	97	88	46	97	88
4	47	97	88	46	97	88	46	97	88
5	47	97	88	46	97	88	46	97	88
6	47	97	88	46	97	88	46	97	88
7	46	97	88	46	97	88	46	97	88
8	47	97	88	46	97	88	46	97	88
9	47	97	88	46	97	88	46	97	88
10	47	97	88	46	97	88	46	97	88

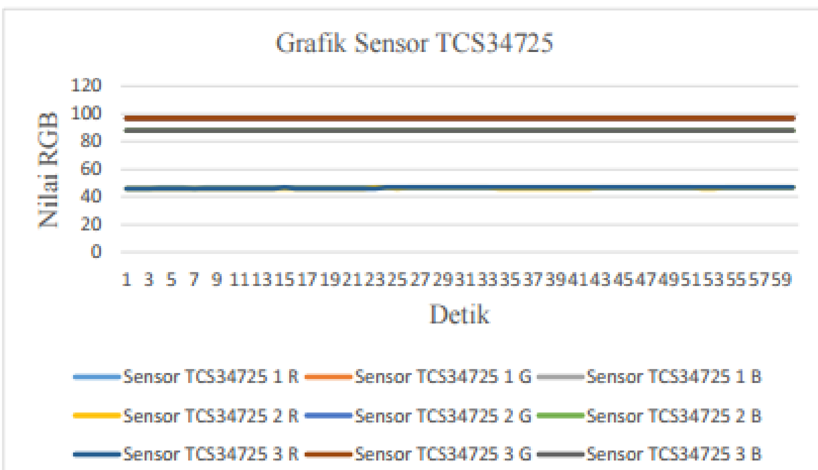

Figure 6. TCS34725 sensor response under static water conditions.

The results indicate that the RGB values generated by the TCS34725 sensor were relatively stable during repeated measurements. The small variation in the red component shows that the sensor had consistent performance in detecting liquid color characteristics. Therefore, the TCS34725 sensor was considered suitable as one of the input parameters for the fuzzy logic system.

Turbidity Sensor Testing

The turbidity sensor was tested to determine its sensitivity to changes in liquid characteristics. The results showed that water produced turbidity values ranging from 969 to 1424 NTU, while biodiesel oil produced values ranging from −300 to −2705 NTU. The difference between these measurement ranges indicates that the turbidity sensor was able to distinguish water from oil-contaminated liquid. Under flowing conditions, fluctuations were observed due to liquid movement, but the sensor still maintained distinguishable reading patterns. The turbidity sensor testing results are presented in Table 2 and Figure 7.

Table 2. Turbidity sensor testing results.

No.	NTU 1	NTU 2	NTU 3
1	1424	1424	1397
2	816	939	999
3	816	939	999
4	939	939	999
5	939	939	999
6	939	939	999
7	939	939	999
8	939	908	999
9	939	908	999
10	939	908	999

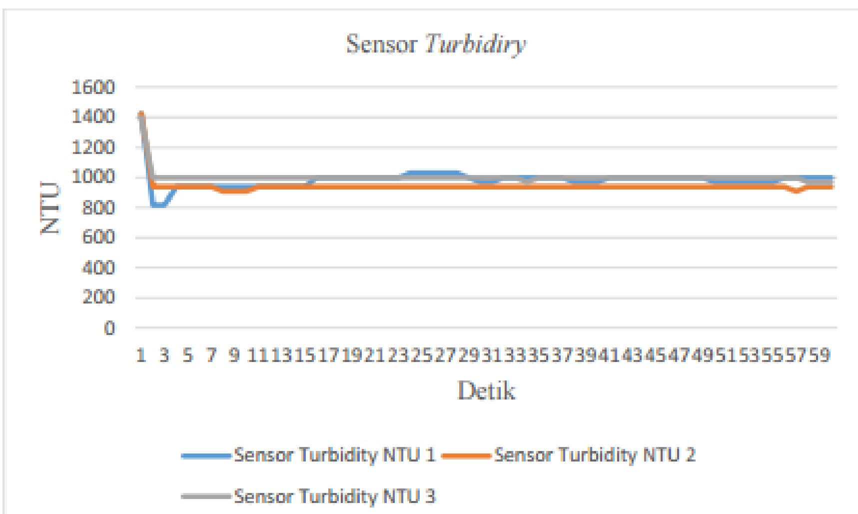

Figure 7. Turbidity sensor response under flowing water conditions.

The turbidity sensor showed a clear response difference between water and biodiesel oil. Although several fluctuations appeared during flowing-liquid testing, the sensor readings remained sufficiently distinct for contamination detection. These results demonstrate that the turbidity sensor can serve as a supporting input for improving the reliability of the oil detection process.

Ultrasonic Sensor Testing

The HC-SR04 ultrasonic sensor was tested by comparing sensor readings with manual measurements using a ruler. The purpose of this test was to evaluate the accuracy of water-level detection in the prototype system. The results showed that the measurement differences ranged from 0.1 cm to 1.0 cm. Most readings showed relatively small deviations, indicating that the ultrasonic sensor had acceptable accuracy for detecting water levels. The sensor was able to classify water-level conditions into full, medium, and low categories. These categories were then used as input variables in the fuzzy logic system to determine pump activation. The ultrasonic sensor testing results are presented in Table 3.

Table 3. Ultrasonic sensor testing results.

No.	Sensor Measurement (cm)	Ruler Measurement (cm)	Difference (cm)
1	5.2	5	0.2
2	5.8	6	0.2
3	7.6	7	0.6
4	8.2	8	0.2
5	8.8	9	0.2
6	11.0	10	1.0
7	11.3	11	0.3
8	12.2	12	0.2
9	13.1	13	0.1
10	14.1	14	0.1

The results indicate that the HC-SR04 sensor was capable of detecting the water level with relatively low measurement error. The obtained readings were then classified into operational categories for pump control. When the water level was classified as full, pump 1 was activated. When the water level was classified as medium, pump 2 was activated. When the water level decreased to the low category, the pumps were deactivated and the gate returned to the open condition.

Sugeno Fuzzy Logic Testing

The Sugeno fuzzy logic method was used as the decision-making system for automatic water gate and pump control. The fuzzy system processed three input variables, namely color sensor values, turbidity sensor values, and ultrasonic sensor readings. The output of the fuzzy system determined whether the water gate should be opened or closed and whether the pumps should be activated or deactivated. The system used eight fuzzy rules to represent the operational logic of oil detection and water-level control. Water-level classification used in the fuzzy logic testing is presented in Table 4.

Table 4. Water-level classification in fuzzy logic testing.

No.	Test	Sensor Value (cm)	Classification
1	Test 1	1–7	Full
2	Test 2	8–13	Medium
3	Test 3	14–21	Low

The MATLAB simulation showed that the Sugeno fuzzy logic model was able to generate decisions according to the sensor input conditions. When oil was detected and the water level was full, the system closed the water gate and activated pump 1. When the water level was medium, pump 2 was activated. When no oil was detected and the water level was low, the system opened the water gate and turned off the pumps. These results indicate that the fuzzy logic controller operated according to the designed rule base.

Overall System Testing

The overall system testing was conducted by flowing water and biodiesel oil through the prototype channel. During normal water conditions, the gate remained open and the pumps were inactive. When oil was detected by the TCS34725 color sensor and turbidity sensor, the fuzzy controller automatically closed the water gate to prevent contaminated liquid from flowing out of the system. After the gate was closed, the ultrasonic sensor detected the water level and activated the pump according to the fuzzy rule base. The integrated system testing results are presented in Table 5 and Figure 8.

Table 5. Overall system testing results.

No.	TCS34725 Sensor	Turbidity Sensor	Ultrasonic Sensor	System Response	LCD Notification
1	Water (45, 98, 88)	Water (999)	Full (6 cm)	Gate open; pumps 1 and 2 off	Displayed on LCD
2	Oil (50, 97, 86)	Oil (−1971 NTU)	Full (6 cm)	Gate closed; pump 1 on	Displayed on LCD
3	Oil (51, 97, 85)	Oil (−1971 NTU)	Medium (7–13 cm)	Gate closed; pump 2 on	Displayed on LCD
4	Empty (81, 85, 88)	Empty (3000)	Medium (7–13 cm)	Gate closed; pump 2 on	Displayed on LCD

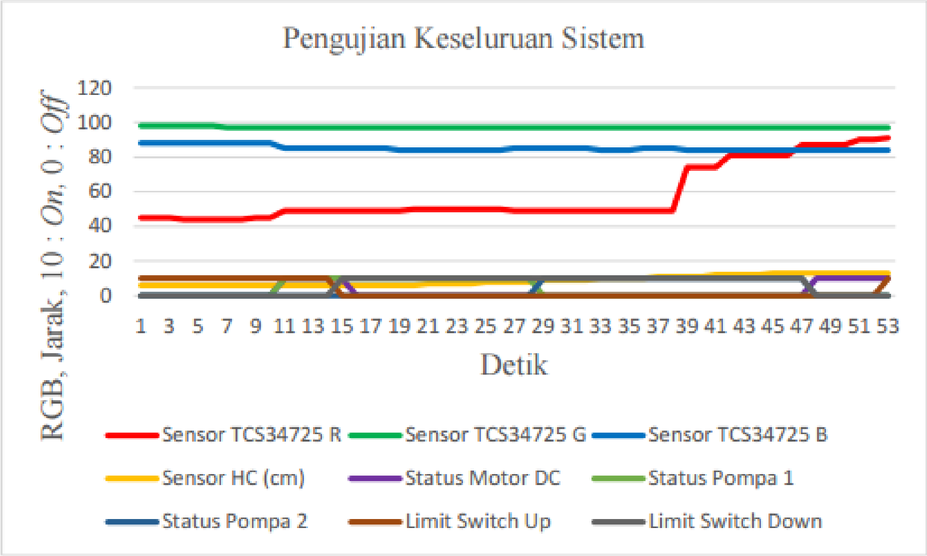

Figure 8. Overall response of the automatic water gate control system.

The overall testing results demonstrate that the developed prototype operated according to the designed system logic. The integration of the TCS34725 color sensor and turbidity sensor enabled the system to identify oil contamination, while the ultrasonic sensor provided water-level information for pump control. When contamination was detected, the water gate automatically closed to isolate the contaminated liquid. The pumps were then activated based on the detected water level. After the contaminated liquid was removed and the water level decreased, the system reopened the water gate and deactivated the pumps. These findings show that the integration of Arduino Uno, multi-sensor input, DC motor actuation, pump control, and Sugeno fuzzy logic successfully produced an automatic water gate control system for biodiesel oil leak monitoring.

Discussion

The findings of this study demonstrate that the proposed multi-sensor fuzzy logic-based automatic water gate control system successfully integrated sensing, intelligent decision-making, and automatic actuation into a single embedded platform for biodiesel wastewater monitoring. The integration of the TCS34725 color sensor, turbidity sensor, and HC-SR04 ultrasonic sensor enabled the system to evaluate multiple physical characteristics of wastewater simultaneously, thereby improving the reliability of contamination detection compared with approaches relying on a single sensing parameter. The successful implementation of the Arduino Uno as the central processing unit further confirms that low-cost embedded platforms can effectively support intelligent environmental monitoring applications while maintaining adequate computational performance for real-time control. The developed prototype also demonstrated stable communication between sensing devices, the Sugeno fuzzy logic controller, and output actuators, allowing automatic responses to contamination events without requiring continuous operator intervention. These findings indicate that combining complementary sensing technologies with intelligent control algorithms can substantially enhance the responsiveness of industrial wastewater management systems. Similar observations have been reported in previous studies, where multi-sensor integration significantly improved measurement reliability and decision accuracy in environmental monitoring and industrial automation applications (Bicamumakuba et al., 2025; Kong et al., 2020; Z. Liu et al., 2022; Zhang et al., 2024). Earlier investigations also demonstrated that integrating heterogeneous sensors provides more comprehensive environmental information than relying on individual sensing devices, particularly under dynamic operating conditions. Nevertheless, most previous studies primarily emphasized monitoring and data acquisition rather than integrating automatic decision-making with real-time mechanical control. In contrast, the present study extends existing research by combining contamination detection, water-level monitoring, fuzzy logic inference, and automatic water gate operation into a unified control framework. Therefore, the developed prototype contributes not only to improving monitoring performance but also to advancing intelligent automation for industrial wastewater management through an integrated multi-sensor control strategy.

The experimental evaluation of the TCS34725 color sensor and turbidity sensor demonstrated that both sensors consistently distinguished biodiesel oil from clean water using different physical characteristics. The TCS34725 sensor identified oil contamination through measurable differences in RGB values, whereas the turbidity sensor differentiated contamination based on variations in optical transparency. The complementary behavior of these two sensors substantially reduced the possibility of misclassification that may occur when only one sensing parameter is employed. This finding supports the principle that sensor fusion enhances detection reliability by combining independent environmental observations into a unified decision-making process. Previous studies investigating optical color sensors for liquid identification reported that RGB-based measurements provide an effective approach for distinguishing liquids with different optical properties under controlled illumination conditions (Kant et al., 2023; Mohebbian et al., 2021). Likewise, investigations involving turbidity sensors have shown that optical scattering characteristics can be effectively utilized to evaluate changes in water quality caused by suspended particles or liquid contaminants. However, many earlier studies employed either color sensing or turbidity sensing independently, limiting their capability to address complex contamination scenarios in industrial wastewater systems. The present study demonstrates that integrating both sensing mechanisms enables more robust contamination detection because each sensor compensates for the limitations of the other under varying wastewater conditions. The stable sensor responses observed during repeated experiments further indicate that the proposed sensing configuration is sufficiently reliable for continuous real-time monitoring applications. Consequently, the integration of color and turbidity sensing provides a practical foundation for intelligent biodiesel oil leak detection while simultaneously improving the operational robustness of the automatic control system.

Another important finding of this study is the successful implementation of the HC-SR04 ultrasonic sensor and the Sugeno fuzzy logic controller for adaptive decision-making during automatic wastewater management. The ultrasonic sensor exhibited relatively small measurement deviations compared with manual measurements, indicating that it provided sufficiently accurate water-level information for operational control. Accurate water-level measurement is essential because the pumping strategy depends not only on contamination detection but also on the available wastewater volume within the drainage channel (Alshami et al., 2023; Lu et al., 2020; Saad et al., 2020). The use of Sugeno fuzzy logic enabled multiple sensor inputs to be processed simultaneously while accommodating uncertainty that commonly exists in environmental monitoring systems. Unlike conventional threshold-based control methods, fuzzy logic considers gradual transitions among different operating conditions, resulting in smoother and more adaptive control decisions. Previous studies have consistently reported that Sugeno fuzzy inference systems offer rapid computational performance and stable control behavior in embedded applications because of their relatively simple mathematical structure. Similar research on intelligent automation has also demonstrated that fuzzy logic effectively improves controller flexibility when multiple environmental variables influence operational decisions simultaneously (Gad et al., 2024; Guler et al., 2024; X. Liu et al., 2025; Tang & Ahmad, 2024). The results obtained in the present study are consistent with these findings, as the developed controller successfully generated appropriate commands for automatic gate movement and pump activation according to predefined operational rules. Furthermore, the integration of fuzzy logic with multi-sensor information reduced dependence on human judgment during contamination events, thereby increasing response speed and operational consistency. Collectively, these results suggest that the proposed intelligent control strategy has considerable potential for supporting safer, more efficient, and environmentally sustainable wastewater management in biodiesel processing facilities.

The overall performance evaluation demonstrated that the proposed intelligent monitoring system successfully executed automatic responses under various contamination scenarios, confirming the effectiveness of integrating sensing technology with embedded control algorithms. During normal operating conditions, the water gate remained open while the pumping system remained inactive, indicating that the controller correctly identified uncontaminated wastewater conditions. Once biodiesel oil was detected by the combined responses of the TCS34725 color sensor and turbidity sensor, the fuzzy logic controller immediately initiated the contamination mitigation process by closing the water gate and activating the appropriate pump according to the measured water level. This coordinated response illustrates the capability of the proposed system to perform both environmental monitoring and automatic operational control within a single embedded platform. Previous studies on industrial wastewater monitoring have primarily focused on monitoring water quality parameters, Internet of Things (IoT)-based data transmission, or predictive analytics without integrating immediate mechanical responses into the monitoring framework (Bandara et al., 2025; Bhardwaj et al., 2022; Silva et al., 2022). Similarly, several oil leak detection systems have emphasized pipeline monitoring using wireless sensor networks (Abubakar et al., 2025; Sayghe, 2025; Sharma et al., 2024; Wong & McCann, 2021), image processing, or deep learning algorithms, whereas their outputs generally provide alarms or notifications rather than direct physical intervention. The present study extends these approaches by introducing an integrated control strategy in which contamination detection is directly linked to automatic gate isolation and wastewater pumping. Such a configuration reduces response time during contamination events and minimizes the possibility of polluted wastewater entering surrounding water bodies before corrective action can be taken. Furthermore, the use of affordable embedded hardware demonstrates that intelligent environmental automation can be implemented without requiring sophisticated industrial control infrastructure. Therefore, the developed system represents a practical alternative for improving industrial wastewater management, particularly for small- and medium-scale biodiesel processing facilities where cost-effective automation solutions are highly desirable.

From a broader perspective, this study provides both scientific and practical contributions to the development of intelligent environmental control systems. Scientifically, the proposed prototype demonstrates that combining multi-sensor integration with Sugeno fuzzy logic produces a reliable decision-making framework capable of simultaneously processing heterogeneous environmental information and generating adaptive control actions. Unlike many previous investigations that examined sensing technologies, fuzzy controllers, or wastewater monitoring independently, this research integrates these components into a unified automation architecture specifically designed for biodiesel wastewater management. The integration strategy also illustrates how complementary sensor information can improve system robustness by reducing uncertainty associated with individual sensor measurements. From an engineering perspective, the developed prototype provides an accessible platform that can be expanded with additional sensors, wireless communication modules, cloud-based monitoring, or artificial intelligence algorithms to support larger industrial applications. The modular architecture employed in this study also facilitates future system upgrades without requiring substantial modifications to the existing control framework. Although the prototype demonstrated stable performance under laboratory-scale conditions, additional validation under real industrial operating environments will be necessary to evaluate long-term reliability, sensor durability, and operational robustness under fluctuating wastewater characteristics. Future studies may also incorporate machine learning or adaptive fuzzy algorithms to improve decision accuracy under more complex environmental conditions and variable contamination patterns. Moreover, integrating Internet of Things technologies with cloud-based supervisory systems could enable remote monitoring, predictive maintenance, and real-time operational optimization for industrial wastewater treatment facilities. Overall, the findings of this study demonstrate that the proposed multi-sensor fuzzy logic-based automatic water gate control system offers a promising and scalable solution for enhancing environmental protection, operational efficiency, and sustainable wastewater management within the biodiesel industry.

Implication

The findings of this study provide important implications for the advancement of intelligent environmental monitoring and automated industrial wastewater management systems. The successful integration of color sensing, turbidity measurement, and water-level detection demonstrates that multi-sensor architectures can improve the reliability of contamination identification compared with approaches that rely on a single sensing parameter. The implementation of the Sugeno fuzzy logic algorithm further confirms its suitability for handling uncertainty in environmental monitoring while enabling adaptive and real-time operational decision-making. From an engineering perspective, the developed prototype offers a practical framework for designing cost-effective embedded control systems capable of simultaneously performing monitoring and automatic response functions. The proposed system also demonstrates that low-cost microcontroller platforms, such as Arduino Uno, can be effectively utilized to develop intelligent automation solutions for industrial wastewater applications without requiring complex control infrastructure. For industrial practitioners, the automatic operation of the water gate and pumping mechanism has the potential to reduce dependence on manual inspection, shorten response times during contamination events, and minimize the release of biodiesel oil into surrounding aquatic environments. These operational improvements may contribute to enhanced environmental compliance, improved wastewater treatment efficiency, and reduced maintenance costs associated with pollution control. The study also contributes to the growing body of knowledge on intelligent control systems by demonstrating the benefits of integrating heterogeneous sensor information within a unified fuzzy logic framework for environmental applications. Furthermore, the modular system architecture facilitates future integration with wireless communication technologies, Internet of Things platforms, cloud-based monitoring systems, and advanced data analytics to support large-scale industrial deployment. The proposed approach therefore provides a valuable foundation for the development of next-generation smart wastewater management systems that combine real-time monitoring with autonomous control capabilities. From a sustainability perspective, the implementation of intelligent automatic monitoring systems may help industries reduce environmental pollution risks while supporting cleaner production practices and responsible wastewater management. Overall, the proposed multi-sensor fuzzy logic-based automatic water gate control system represents a scalable and adaptable technological solution that can support the digital transformation of industrial environmental management and contribute to more sustainable biodiesel production.

Limitation and Suggestion for Further Research

Although the proposed multi-sensor fuzzy logic-based automatic water gate control system demonstrated satisfactory performance under laboratory-scale conditions, several limitations should be acknowledged when interpreting the findings of this study. First, the experimental evaluation was conducted using a prototype with controlled testing scenarios that may not fully represent the complexity and variability of real industrial wastewater environments. Second, the system was validated using biodiesel oil and clean water samples, whereas actual industrial wastewater may contain additional contaminants, suspended solids, chemicals, and fluctuating physicochemical properties that could influence sensor performance and control accuracy. Third, the sensing configuration relied on three sensor types, which, although effective for the intended application, may not capture all environmental parameters required for comprehensive wastewater quality assessment. In addition, the implemented Sugeno fuzzy logic controller utilized predefined membership functions and rule bases that remained static throughout the experimental process and therefore did not adapt automatically to changing environmental conditions. The prototype also operated as a standalone embedded system without wireless communication capabilities or remote monitoring functions, limiting its applicability for large-scale industrial supervision. Furthermore, long-term operational reliability, sensor durability, and maintenance requirements were not evaluated because the experiments were performed over a relatively short testing period. Future studies should validate the proposed system under actual industrial operating conditions involving continuous wastewater discharge and diverse contamination scenarios to assess its practical robustness. Additional sensing technologies, such as pH, dissolved oxygen, electrical conductivity, temperature, or hydrocarbon concentration sensors, should also be integrated to improve the comprehensiveness of wastewater monitoring. Future research may further enhance system intelligence by incorporating adaptive fuzzy systems, machine learning algorithms, or hybrid artificial intelligence approaches capable of automatically optimizing decision rules based on historical operational data. The integration of Internet of Things technologies, cloud computing platforms, and real-time supervisory dashboards is also recommended to facilitate remote monitoring, predictive maintenance, and centralized environmental management across multiple industrial facilities. Overall, addressing these limitations and implementing the proposed improvements will contribute to the development of more accurate, scalable, and intelligent wastewater automation systems capable of supporting sustainable biodiesel production and advanced industrial environmental management.

CONCLUSION

This study successfully developed a multi-sensor fuzzy logic-based automatic water gate control system for real-time biodiesel oil leak monitoring using an Arduino Uno embedded platform. The proposed system integrated a TCS34725 color sensor, a turbidity sensor, and an HC-SR04 ultrasonic sensor to simultaneously monitor wastewater color characteristics, turbidity, and water level. Experimental results demonstrated that the TCS34725 sensor consistently differentiated biodiesel oil from clean water through distinct RGB values, while the turbidity sensor provided complementary information by identifying differences in liquid transparency. The HC-SR04 ultrasonic sensor also exhibited satisfactory measurement accuracy for monitoring water-level conditions required for automatic pump operation. The implementation of the Sugeno fuzzy logic algorithm enabled the system to process multiple sensor inputs simultaneously and generate adaptive control decisions for automatic water gate movement and pump activation. Integrated system testing confirmed that the developed prototype successfully responded to contamination events by isolating polluted wastewater and operating the pumping mechanism according to predefined fuzzy rules. The combination of multi-sensor integration and intelligent control significantly enhanced the capability of the prototype to perform continuous environmental monitoring and automatic operational responses within a single embedded system. The developed prototype also demonstrated stable communication among sensing devices, the microcontroller, and actuator components throughout the experimental evaluation. These findings indicate that the proposed system provides an effective and reliable approach for supporting automated biodiesel wastewater management while reducing dependence on manual monitoring. In addition, the use of affordable embedded hardware highlights the feasibility of implementing intelligent environmental control technologies in industrial applications with limited infrastructure resources. The proposed system therefore contributes to the advancement of intelligent wastewater automation by integrating environmental sensing, fuzzy logic-based decision-making, and real-time mechanical control into a unified operational framework. Overall, this study demonstrates that the proposed automatic water gate control system represents a promising technological solution for improving environmental protection, operational efficiency, and sustainable wastewater management in biodiesel processing industries.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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