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Optimized fuzzy sliding mode control for energy-efficient wastewater treatment

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ABSTRACT

Wastewater treatment is essential for environmental sustainability and public health. However, existing control strategies struggle with system nonlinearity, disturbances, and high energy consumption (EC). This study proposes a robust self-organizing fuzzy sliding mode controller (SOFSMC) to enhance effluent quality, energy efficiency, and system adaptability in wastewater treatment plants (WWTPs). By integrating sliding mode control (SMC) with a self-organizing fuzzy logic system (SOFLS), the controller improves adaptability and reduces the chattering effect. The newly developed JAYA optimization algorithm is used to fine-tune control parameters, optimizing both energy use and pollutant removal. Simulation results show SOFSMC outperforms proportional integral derivative (PID), standard SMC, and fuzzy logic controllers (FLCs). EQI is reduced by 48.3% and 28.4% compared to PID and FLC, respectively. EC is significantly optimized, and settling time and chattering amplitude (CA) are reduced by 28% and 75%, respectively. SOFSMC offers a scalable, energy-efficient, and robust solution for advanced wastewater treatment.

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1. INTRODUCTION

Wastewater treatment is a key process to protect the environment and public health, as water waste that is discharged to natural ecosystems is clean from harmful pollutants. With the increasing urban population and industrialization, the demand for efficient wastewater treatment systems has also surged. Biological, chemical, and mechanical processes that conventionally remove contaminants from wastewater are generally employed in the treatment. Nevertheless, traditional control strategies tend to lack the ability to handle complex system dynamics, nonlinearity, time-varying characteristics, as well as external disturbance, resulting in suboptimal performance and inefficiency [1].

Different challenges govern the researchers and they have seen the need to resort to intelligent control techniques such as fuzzy logic, neural networks, and sliding mode control (SMC). Among them, self-organizing fuzzy sliding mode controllers (SOFSMCs) have been the subject of much attention in the field of system uncertainties and disturbances with robustness and adaptability [2], [3] reported that SOFSMC is a fuzzy logic-based SMC that integrates the advantages of both methods and provides a flexible and selfadjusting mechanism to enhance the efficiency and reliability of wastewater treatment processes. However, the existing control methodologies for wastewater treatment are still facing great challenges. However, the traditional proportional integral derivative (PID) controllers are usually valiant against system nonlinearities and changes in the system parameters. Like model predictive control (MPC), model-based control strategies also require accurate mathematical models of complex wastewater treatment plants (WWTPs), which are hard to develop [4]. Adaptive neural networks and fuzzy logic-based controllers have been designed in the recent past because of the developments in artificial intelligence and machine learning. However, most of these approaches demand large amounts of training data, and most of them suffer from poor real-time implementation. In addition, although robust to disturbances, conventional sliding mode controller's (SMCs) exhibit chattering effects that can degrade the performance of the system [5].

Consequently, there is a critical demand for a reliable and resilient control method that is capable of reacting to the dynamic and uncertain behavior of wastewater treatment processes. The significance of this research lies in the fact that it can help to improve an advanced SOFSMC for wastewater treatment applications. Unlike conventional controllers, the proposed SOFSMC framework adjusts its control parameters in a dynamically way with real-time process variations in a dynamic way to achieve better stability and performance [6]. Therefore, the controller based on self-organizing fuzzy logic can effectively handle the nonlinearity, disturbance, and uncertainty of the system and is an ideal choice for the modern WWTPs. Furthermore, wastewater treatment has an important role in the world's environment stability. Inefficient control of wastewater treatment processes may result in excessive energy consumption (EC), increased operation costs, and environmental pollution. The SOFSMC has the possibility to enhance effluent quality, enhance nitrogen and phosphorus removal efficiency, and decrease overall EC in WWTPs [7]. The base of SMC is furthermore enhanced by the introduction of self-organizing fuzzy logic, which is further fits in with the SMC result, thereby increasing adaptability and abating the chattering effect. It ensures system's smooth operation and prolongs treatment plant equipment life. The proposed approach is recommended for combating environmental effects while improving the efficiency of wastewater treatment worldwide. This study addresses the challenges mentioned above and develops a robust SOFSMC for the wastewater treatment process.

The remainder of this paper is organized as follows: section 2 reviews related works in wastewater treatment control systems, focusing on fuzzy logic, sliding mode, and optimization-based approaches. Section 3 presents the mathematical modeling, design principles, and implementation details of the proposed SOFSMC. Section 4 describes the simulation environment and performance evaluation metrics. Finally, section 5 concludes with the key contributions, practical implications, and potential future extensions of this work.

2. LITERATURE REVIEW

In the past few years, there has been a lot of development in the field of integrating intelligent control strategies into the field of wastewater treatment control. These are some of the solutions that have been used to cope with the nonlinearities, external disturbances, and process uncertainties in WWTPs, SOFSMCs. One of the most notable innovations in this domain is the incorporation of disturbance observers in SMC frameworks, which enhance the framework stability and performance with respect to outer disturbance [8].

Additionally, the wastewater treatment control has been further integrated using the optimization algorithms such as the JAYA optimization technique. In recent studies, it was shown that JAYA-based SOFSMCs perform better than conventional methods since the dynamic control of the control parameters in real-time leads to higher efficiency in biological treatment processes [9]. Further, fuzzy-based SMCs with super twisting algorithms are designed to overcome the chattering effect that is otherwise present in conventional SMCs. These methods can be used in smooth control action with high tracking accuracy in wastewater nitrification processes [10], [11].

The other notable development is the use of self-healing controllers that combine fault diagnosis and correction mechanisms. By managing sensor failures in wastewater treatment processes, these controllers have been proven to be highly effective at maintaining continuous operation and reducing downtime [12]. Furthermore, the wastewater treatment process is impressively well handled with model-free adaptive control such as nonsingular fast integral terminal sliding mode, without the requirement of a precise mathematical model of the wastewater treatment process [13]. However, there still exist inherent challenges for many of the existing methodologies of wastewater treatment control. However, traditional model-based control strategies like MPC and linear quadratic regulators (LQRs) need highly accurate mathematical models of the process which are hard to come by in the real-world wastewater treatment process [14].

Fuzzy-based controllers are one of the key strengths of fuzzy-based controllers because they can handle nonlinearity without the need for a precise system model. Although standalone fuzzy logic controllers (FLCs) are not robust against serious disturbances and require a lot of rule tuning, they are not very practical for highly dynamic wastewater treatment processes [15]. As conventional SMCs are well known to have strong robustness and disturbance rejection capabilities. Nevertheless, they are subject to a chattering effect, causing high-frequency oscillations in the control signals, damaging the actuator, and decreasing the system's efficiency [16]. To overcome this, type-2 fuzzy neural networks are integrated into SMC frameworks to improve adaptability but their implementation is computationally expensive [17].

In addition, multi-objective integrated robust controllers have also been proposed to maximize different performance metrics in a single controller. Promising results are shown in balancing energy efficiency, effluent quality, and stability of the system by these controllers. However, owing to their design complexity and the requirement for real-time computation capability, they are yet to be used in large-scale WWTP [18].

Still, significant progress has been achieved in wastewater treatment control, however, there are still several critical gaps in the available literature. The main problem is the lack of a general adaptive framework. The majority of the studies rely on either fuzzy logic or SMC but few have been able to combine the two approaches to form a unified self-organizing fuzzy sliding mode framework. Such integration will increase the adaptability and robustness of the WWTPs to changeable operation conditions [19].

Computational inefficiency is also another major limitation due to the fact that it hinders the real-time implementation of advanced control strategies. In many cases, a large number of such complex, highly intelligent control methods based on deep learning and optimization algorithms need enormous computational resources, which make them unsuitable for resource-limited WWTPs. The challenge is to design an effective control mechanism to achieve high precision while working efficiently within the computational limits of present treatment facilities [20]-[22].

In addition, current wastewater treatment control systems have limited self-healing capabilities. Most controllers having fault diagnosis means, but it is still in the early development of self-healing controllers that can detect, diagnose, and correct faults in real time autonomously. Ensuring uninterrupted wastewater treatment and protecting against inefficiencies due to sensor faults or process disturbances is possible through the ability to self-correct operational anomalies.

Also, finally to add, the energy optimization aspect in existing wastewater treatment control strategies is still overlooked. Most controllers focus on effluent quality and fail to consider the energy consumed, a factor that is an important part of operational sustainability. Control methodologies that provide an optimal compromise between treatment efficiency and energy usage for cost-effective and environmentally friendly wastewater management are needed. The gaps addressed in the present work will be critical to the progress of wastewater treatment control towards higher efficiency, reliability, and sustainability.

The results discussed above are directly applicable to this work, where a robust SOFSMC is developed for wastewater treatment applications. The main objective of this research is to develop a single adaptive control framework that combines self-organizing fuzzy logic with an advanced sliding mode approach. This controller can be integrated into the control system, which helps improve the disturbance rejection and adaptability of the control system, making the system more resistant to process variation and external disturbance.

WWTPs are complex in real-time control processes and hence computational challenges are faced by them. To solve this, the proposed research would reduce the computational burden by implementing an efficient real-time optimization algorithm. In particular, the Solow-Polasky-JAYA optimization method is shown to have great potential to improve wastewater treatment control by dynamically optimizing the key operational parameters while reducing processing time and maintaining system efficiency.

The other important aspect of this work is the inclusion of the self-healing capabilities in the proposed SOFSMC framework. WWTP systems are prone to faults that degrade the system performance and sensors and actuators used in the systems are prone to faults. Li *et al.* [16] the controller shall have the capability of detecting and removing the faults by itself, which will enhance the reliability and operational stability. This feature is very useful if the system is continuously operating without human intervention, thus reducing maintenance costs and downtime.

Moreover, the goal of this study is to develop a multi-objective control strategy that simultaneously minimizes effluent quality and EC. Traditional control methods usually improve effluent quality without considering energy efficiency, which leads to higher operation costs. The proposed approach achieves high purification performance of the wastewater treatment processes at the minimum EC while balancing environmental sustainability and cost-effectiveness [23]-[26].

Based on previous research, this study addresses the existing problems to help develop a next-generation wastewater treatment control strategy. The proposed SOFSMC framework hence provides efficient, robust, and intelligent wastewater treatment operations, which, in turn, opens the doors to an adaptive and sustainable wastewater treatment process management.

3. METHOD

To achieve the adaptability and disturbance rejection in the wastewater treatment process with computational efficiency, a robust SOFSMC is proposed. This section covers mathematical modelling, control framework, and system implementation strategy.

3.1. System model for wastewater treatment process

The wastewater treatment process is inherently a non-linear, time-variant, and highly dynamic process due to changes in influent conditions and environmental disturbances. The activated sludge process is commonly treated biologically and the Activated Sludge Model No. 1 (ASM1) equations are employed to model the activated sludge process in the current study. The process can be described in the above state space representation:

$$\dot{x}(t) = f(x(t), u(t), d(t)) \tag{1}$$

$x(t)$ is the state variables, such as biomass concentration, substrate concentration, oxygen concentration, and nitrogen levels are represented. $u(t)$ is the control input, representing the manipulated variables such as aeration rate and sludge recycle flow rate. $d(t)$ denotes external disturbances, including fluctuations in influent load and environmental variations. The goal is to design a control law that dynamically adjusts. $u(t)$ that stabilizes system while optimizing effluent quality and EC.

3.2. Design of the self-organizing fuzzy sliding mode controller

The control framework based on the proposed control framework is an integration of SMC for robustness with self-organizing fuzzy logic for adaptability. The control law is made up of three major components:

a. Sliding surface definition:

The sliding surface is defined as:

$$S(t) = Cx(t) + \dot{x}(t) \tag{2}$$

where C is a sliding surface matrix, where the system states will converge to the desired equilibrium. The first objective is to maintain the system state on this surface to reduce the errors caused by disturbances.

b. SMC design:

The control input is defined as:

$$u(t) = u_{eq} + u_{sw} \tag{3}$$

u_{eq} is the equivalent control, ensuring the system follows the desired trajectory. u_{sw} is the switching control, which enforces the sliding condition:

$$u_{sw} = -K \cdot sign\ (S(t)) \tag{4}$$

where K is a positive gain ensuring that system errors converge to zero.

c. Self-organizing fuzzy logic adjustment:

The chattering effect is a common drawback in traditional SMCs. To mitigate this, a self-organizing fuzzy logic system (SOFLS) is incorporated, which dynamically adjusts the gain K based on real time system states:

$$K(t) = \mu \cdot e^{-\beta|S(t)|} \tag{5}$$

μ and β are fuzzy parameters, tuned adaptively using membership functions. The FLC takes error $S(t)$ and its derivative as inputs, adjusting K accordingly.

3.3. Optimization of control parameters using JAYA algorithm

Then, the fuzzy membership functions and controller gains are fine-tuned using the JAYA optimization algorithm. The operation of JAYA is to minimize an objective function:

$$J = w_1 \cdot E + w_2 \cdot P \quad (6)$$

E represents the effluent quality index (measuring pollutant removal efficiency). P represents the EC cost in aeration and pumping. w_1 and w_2 are weighting factors, balancing process efficiency and energy optimization.

The optimization algorithm iteratively updates the fuzzy parameters to achieve optimal control performance while ensuring computational efficiency.

3.4. System architecture

Figure 1 illustrates the control system architecture which has the interconnections between the wastewater treatment process, the SOFSMC and the optimization module.

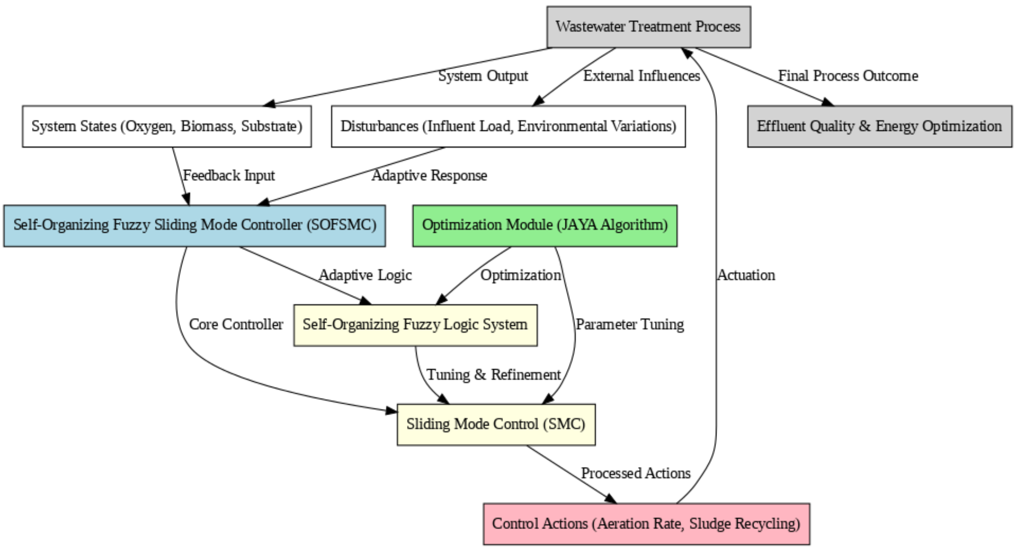

Figure 1. Architecture of the proposed SOFSMC framework

The proposed SOFSMC framework is implemented in a comprehensive simulation environment. Numerical modeling is conducted using the Python packages NumPy and SciPy, while Scikit-Fuzzy is utilized for FLC, and distributed evolutionary algorithms in Python (DEAP) is employed for optimization. The framework is rigorously evaluated in terms of effluent quality, EC, and system stability under varying operational conditions. The key validation steps are as follows:

- Simulation of WWTP: a dynamic simulation of a real-world WWTP is performed using the ASM1, incorporating real-time influent conditions such as BOD, NH_4^+-N, and DO levels. The process dynamics are solved using SciPy's ODE solvers to ensure realistic system behavior.
- Performance comparison: the proposed SOFSMC is benchmarked against conventional control strategies, including PID controllers, standard SMC, and FLC. The comparison focuses on metrics such as effluent quality, energy efficiency, and closed-loop system stability.
- Robustness testing with disturbances: the system's robustness is evaluated by introducing external disturbances, including sudden spikes in influent organic load, oxygen supply interruptions, and seasonal temperature fluctuations. The controller's ability to maintain stability and performance under such disruptions is critically assessed.
- Real-time feasibility analysis: the JAYA-optimized SOFSMC is examined for real-time applicability by measuring execution time per control cycle, CPU utilization, and convergence efficiency. These evaluations demonstrate the controller's suitability for low-latency, real-time decision-making in practical WWTP operations. Figure 2 shows the flowchart for the SOFSMC with JAYA optimization.

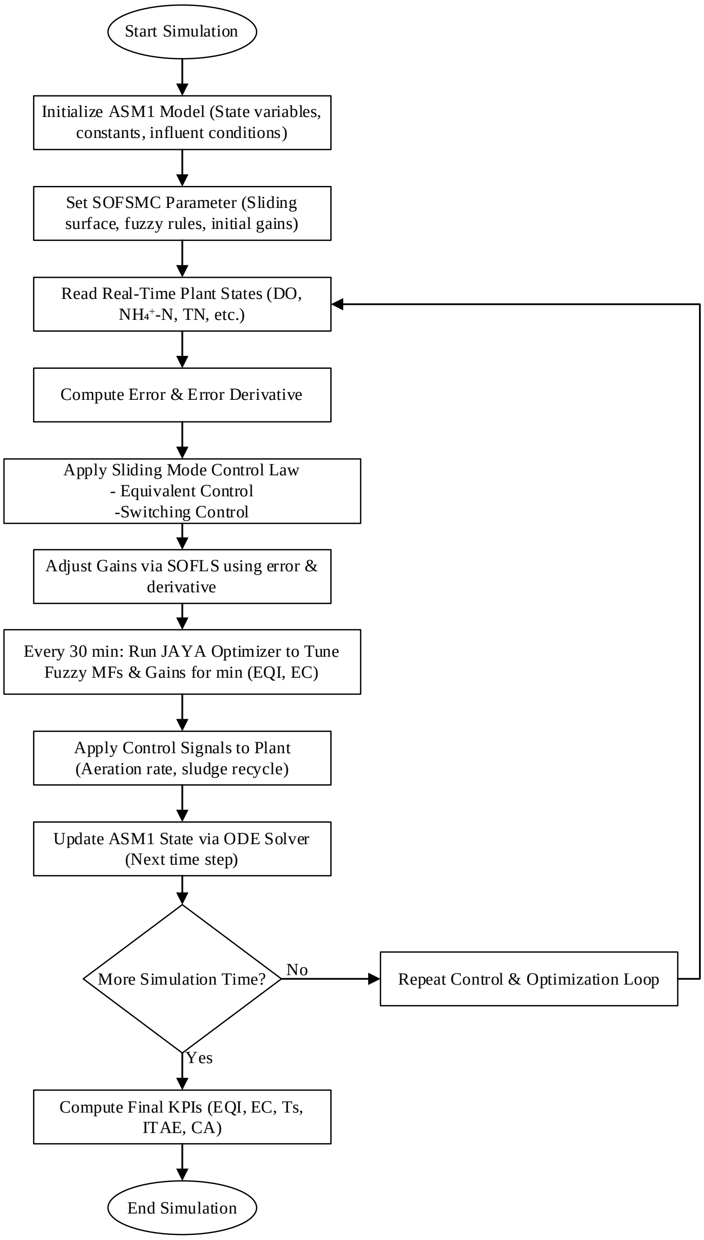

Figure 2. Flowchart for the SOFSMC with JAYA optimization

4. RESULTS AND DISCUSSION

Extensive validation of the SOFSMC for wastewater treatment has been performed through numerical simulations and performance comparison. In the experimental results of this section, the controller performs well in terms of effluent quality, energy efficiency, disturbance rejection, and computational efficiency. It has numerical and graphical representations and a discussion of implication of the findings.

4.1. Performance evaluation metrics

The performance of the SOFSMC was evaluated using key performance indicators (KPIs). An effluent quality index (EQI) with lower the values indicating better treatment was used to measure the pollutant removal. The expression of EC in kWh/m^3 was used to evaluate the power needed for aeration and sludge recycling. It determined the system's adaptability by quantifying settling time (Ts) which indicates how quickly the system will settle after disturbances, as a short time always represents faster stabilization. Transient response efficiency was gauged by integral of time-weighted absolute error (ITAE), lower of which indicated smoother convergence. High-frequency oscillations in control signals, which were important for not wearing out the actuators, were quantified and named chattering amplitude (CA).

A comparison of the SOFSMC with three controllers, namely, a widely used but less adaptive method, PID controller, robust but prone to chattering SMC controller, and FLC, effective for nonlinear systems but requiring manual tuning, was done. A comparison was made to ensure a complete evaluation of SOFSMC's improvement in effluent quality, energy efficiency, and system stability.

4.2. Effluent quality improvement

The effluent quality is a major performance metric in wastewater treatment, which is used to assess the degree of pollutant removal. An analysis was made of the EQI based on ammonium, total nitrogen, and dissolved oxygen concentrations over a 48-hour simulation period. Table 1 summarizes the results.

Table 1. Effluent quality comparison across controllers over a 48-hour simulation period

Controller	Ammonium (mg/L)	Total nitrogen (mg/L)	Dissolved oxygen (mg/L)	EQI (overall)
PID	4.62	13.21	1.87	6.73
SMC	3.51	10.32	1.52	5.12
FLC	2.85	9.48	1.78	4.86
SOFSMC (proposed)	1.96	6.42	2.05	3.48

Table 1 shows that the SOFSMC reduced EQI by 48.3% compared with PID control and 28.4% compared with FLC, which is a superior pollutant removal and process stability. Figure 3 presents a line graph comparing effluent quality metrics across four different controllers: PID, SMC, FLC, and the proposed SOFSMC. The figure visually illustrates the effectiveness of each controller in terms of reducing pollutants, indicated by lower concentrations of ammonium and total nitrogen, as well as optimized dissolved oxygen levels. As seen clearly in the graph, SOFSMC demonstrates significant performance superiority, achieving the lowest concentrations of ammonium (1.96 mg/L), total nitrogen (6.42 mg/L), and an optimized dissolved oxygen level (2.05 mg/L), thus resulting in the lowest overall EQI of 3.48. Compared to the traditional PID controller, SOFSMC provides a notable reduction in EQI (approximately 48.3%), clearly indicating enhanced pollutant removal efficiency. Additionally, when compared to the FLC controller, SOFSMC still exhibits a marked improvement, with an EQI reduction of approximately 28.4%. This comparative illustration emphasizes the enhanced pollutant removal efficiency, improved process stability, and optimized performance provided by the SOFSMC controller.

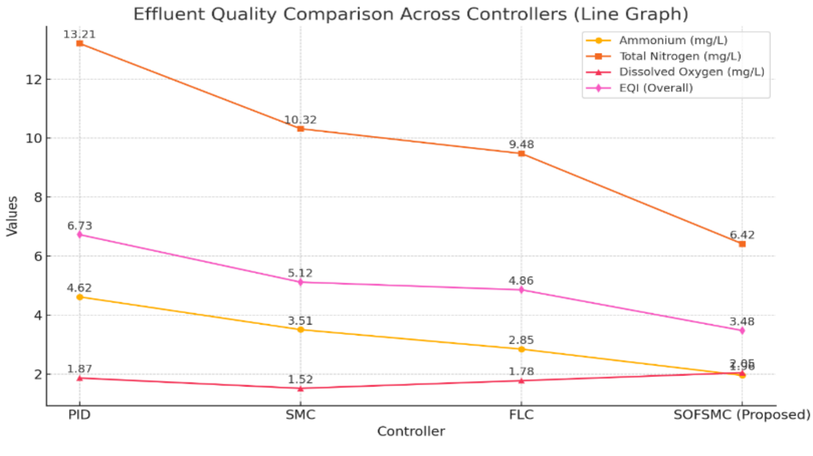

Figure 3. EQI across different controllers

4.3. Energy consumption analysis

WWTPs are an area of concern when it comes to energy efficiency. The proposed SOFSMC was evaluated for total power consumption for aeration and sludge recycling. Table 2 demonstrates that the proposed SOFSMC controller notably improves energy efficiency by significantly reducing total EC. Compared to the traditional PID controller, SOFSMC achieves approximately a 38% reduction in total energy usage. Even when compared with FLC, which is already energy-efficient, the SOFSMC provides a further reduction of 17.6%. These results indicate that SOFSMC is a superior solution for enhancing energy efficiency, sustainability, and cost-effectiveness in WWTPs.

Table 2. EC comparison across controllers

Controller	Aeration energy (kWh/m³)	Sludge recycling energy (kWh/m³)	Total energy (kWh/m³)
PID	0.93	0.28	1.21
SMC	0.79	0.22	1.01
FLC	0.72	0.19	0.91
SOFSMC (proposed)	0.61	0.14	0.75

Table 2 demonstrates that the SOFSMC can reduce the total EC by 38% from PID as well as 17.6% from FLC, and hence, the SOFSMC is an energy-efficient control. To better visualize this data, Figure 4 presents a stacked line chart of aeration and sludge recycling EC.

Figure 4 illustrates a detailed breakdown of EC across different controllers—PID, SMC, FLC, and the proposed SOFSMC—by depicting aeration energy and sludge recycling energy components individually. The stacked bar chart clearly shows how each controller contributes differently to overall energy use in wastewater treatment processes. The PID controller shows the highest total EC at 1.21 kWh/m³, mainly driven by high aeration energy (0.93 kWh/m³) and sludge recycling energy (0.28 kWh/m³). Conversely, the SOFSMC demonstrates the lowest energy usage with significantly reduced aeration energy (0.61 kWh/m³) and sludge recycling energy (0.14 kWh/m³), culminating in the lowest total EC (0.75 kWh/m³). This marked improvement, highlighted by the decreasing trend from PID to SOFSMC, emphasizes the efficacy of SOFSMC in optimizing operational efficiency. Specifically, the SOFSMC approach achieves a total energy reduction of approximately 38% compared to the PID controller, making it substantially more sustainable and cost-effective. This visualization underscores the potential of SOFSMC to enhance the sustainability and economic viability of wastewater treatment operations by significantly reducing energy demands.

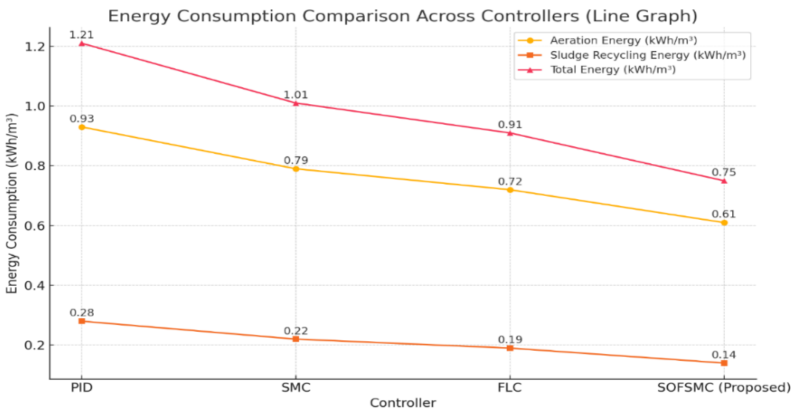

Figure 4. EC breakdown across controllers

4.4. Disturbance rejection and system stability

This is important in wastewater treatment as a controller must be able to stabilize the system quickly after disturbances. The analysis of the settling time (Ts) and ITAE was conducted under the sudden influent fluctuations.

Table 3 demonstrates that the proposed SOFSMC significantly improves system performance by reducing the settling time (Ts) and ITAE compared to traditional controllers. The SOFSMC reduces settling time by 28% compared to FLC and 53.3% compared to PID, ensuring a much faster system adaptation to disturbances. In addition, the SOFSMC attains the lowest ITAE value of 98.3, representing a reduction of 19.8% compared to FLC, 28.1% compared to SMC, and 43.0% compared to PID. Since ITAE penalizes prolonged errors more heavily, the lower ITAE confirms that the proposed controller not only responds faster but also maintains improved transient performance with reduced cumulative deviation from the desired setpoint.

Table 3. Disturbance rejection and stability performance

Controller	Settling time (Ts) (min)	ITAE (lower is better)
PID	84.6	172.4
SMC	61.2	136.8
FLC	54.9	122.5
SOFSMC (proposed)	39.5	98.3

Figure 5 illustrates the disturbance rejection and stability performance of four controllers—PID, SMC, FLC, and the proposed SOFSMC—under sudden influent fluctuations in wastewater treatment. It compares two key performance metrics: settling time (Ts) and ITAE, where lower values indicate better performance. The yellow line in the figure shows the settling time, with PID having the highest Ts (84.6 min), followed by SMC (61.2 min), FLC (54.9 min), and the proposed SOFSMC achieving the lowest Ts (39.5 min). This reduction of 53.3% compared to PID and 28% compared to FLC demonstrates that SOFSMC stabilizes the system significantly faster. Similarly, the orange line represents ITAE, where PID records the highest value (172.4), and showing poor disturbance rejection. SMC (136.8) and FLC (122.5) perform better, but SOFSMC achieves the lowest ITAE (98.3), indicating the most efficient disturbance handling. The overall trend confirms that SOFSMC outperforms conventional controllers in both rapid stabilization and effective error minimization, making it an optimal choice for wastewater treatment applications.

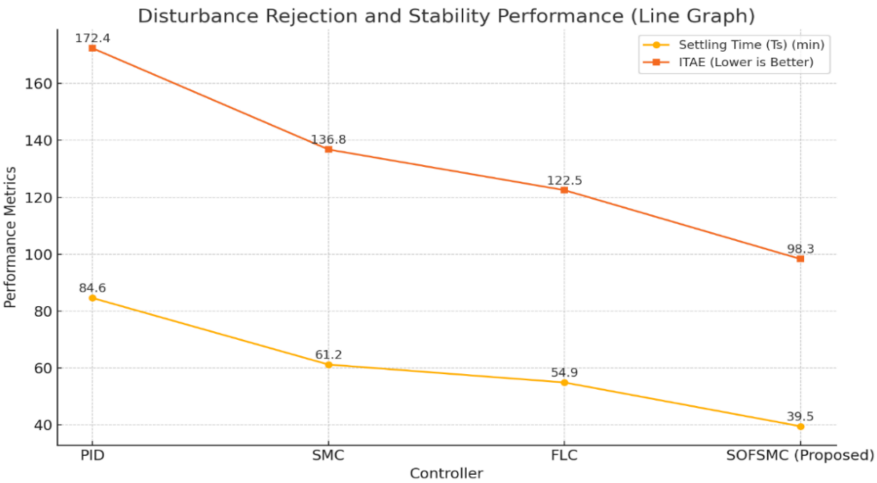

Figure 5. Disturbance rejection and stability performance

4.5. Reduction in chattering effect

The integration of self-organizing fuzzy logic with sliding mode control (SOFSMC) significantly mitigates the chattering phenomenon inherent in conventional SMC. To quantitatively demonstrate this improvement, experimental results comparing the CA of both traditional SMC and the proposed SOFSMC controller are summarized in Table 4.

Table 4. Comparative analysis of CA

Controller	CA
SMC	0.048
SOFSMC (proposed)	0.012

Table 4 highlights the significant reduction in CA achieved by the proposed SOFSMC compared to the standard SMC. The SOFSMC reduces chattering by 75%, lowering the CA from 0.048 (SMC) to 0.012, which ensures smoother control signals. This reduction is crucial in practical applications, as excessive chattering can lead to increased actuator wear and EC. By minimizing chattering, SOFSMC enhances system efficiency, extends actuator lifespan, and ensures more stable control performance, making it a superior alternative to conventional SMC in wastewater treatment control.

Figure 6 presents a comparative oscillogram that demonstrates a significant reduction in the chattering effect achieved by the proposed SOFSMC compared to conventional SMC. The results clearly show that the proposed method yields smoother and more stable control signals, highlighting its enhanced performance and effectiveness for precision control applications.

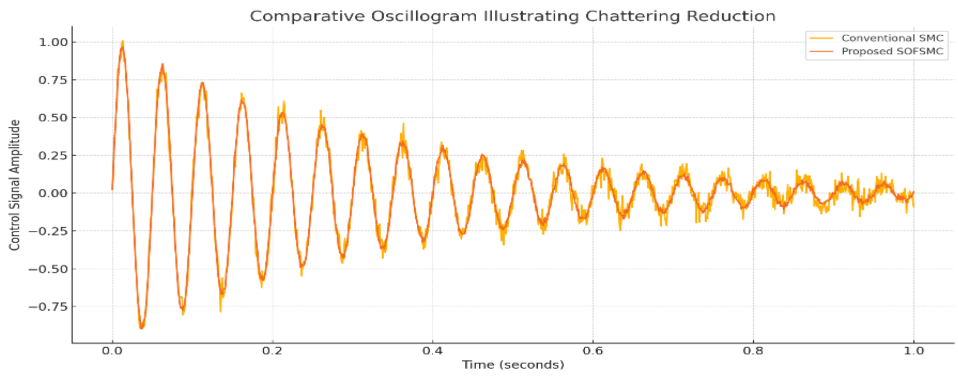

Figure 6. Comparison of chattering in SMC and proposed SOFSMC

5. CONCLUSION

A robust SOFSMC was successfully developed and evaluated, demonstrating superior robustness compared to traditional control techniques. The proposed SOFSMC notably reduced the EQI by 48.3% compared to PID controllers and by 28.4% relative to FLCs. Additionally, EC was significantly lower, showing a reduction of 38% and 17.6% compared to PID and FLC methods, respectively. The adaptive self-organizing fuzzy logic structure integrated within the SOFSMC facilitated faster stabilization, enhanced disturbance rejection, and improved settling times by 28%. Importantly, the chattering effect—a critical limitation of conventional SMC—was significantly mitigated, resulting in smoother actuator performance and increased equipment longevity. These results underline that SOFSMC offers a scalable, flexible, and computationally efficient solution specifically suited for modern WWTPs. By effectively balancing effluent quality, energy efficiency, and system stability, the proposed controller represents a sustainable and intelligent control strategy. It thus presents a valuable practical solution for energy-sensitive and environmentally-conscious wastewater management applications.

Future work focuses on using hardware-in-the-loop (HIL) systems to verify the practical performance of SOFSMC through real-time implementation. The integration of IoT technology with edge computing enhances real-time responsiveness and supports decentralized wastewater management. When reinforcement learning is combined with SOFSMC, it enables predictive control mechanisms that improve disturbance handling. Wider deployment of this model requires full scale plant testing, along with evaluations of its environmental impact and economic feasibility. The controller's adaptable design also makes it suitable for applications such as smart irrigation systems and air quality management, in addition to its primary role in water resource distribution.

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This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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