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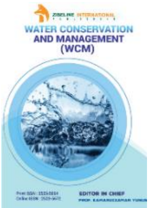

*RESEARCH ARTICLE*

# AUTOMATION SYSTEM AND CONTROL OF QUALITY MONITORING INSTRUMENTS FOR DRINKING WATER DISINFECTION USING CORONA DISCHARGE METHOD

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## ABSTRACT

This study addresses the automation of a corona discharge-based drinking water disinfection system and its control using water quality monitoring tools. The research proposes an automated control system that dynamically adjusts the corona discharge parameters based on water quality parameters (pH, turbidity, electrical conductivity). The following key results were obtained: the system consistently maintained microorganism inactivation efficiency between 99,9% and 99,99%, even under fluctuating water quality conditions. For instance, at a turbidity level of 10 NTU, the disinfection efficiency dropped to 99,8%, while at pH values ranging from 6,5 to 8,5, the efficiency remained between 99,9% and 99,99%. The energy consumption was 20%-35% lower compared to traditional methods; for example, the energy consumption for UV irradiation methods ranged from 0,05 to 0,15 kWh/m3, while the corona discharge method remained between 0,5 and 2,0 kWh/m3. The initial models and control algorithms improved the system's performance in real-time, ensuring stable operation despite changes in water quality parameters. The results demonstrate the significant advantages of the corona discharge method in terms of energy efficiency and stability, proving its ability to maintain high disinfection efficiency even with continuous variations in water quality. Furthermore, this system provides an environmentally friendly and energy-efficient solution for drinking water disinfection.

**KEYWORDS**

Corona discharge, water disinfection, automated control, water quality, energy efficiency, microorganism inactivation, plasma technologies, environmental impact, laboratory modeling, feedback system.

## 1. INTRODUCTION

Ensuring the microbiological safety of drinking water is currently one of the key scientific fields in environmental engineering, applied physics, and automation. According to the World Health Organization, over 2.2 billion people globally use drinking water that does not meet sanitary standards, and waterborne infectious diseases cause approximately 485,000 deaths annually (World Health Organization. 2023 ; World Health Organization. 2023). These statistics highlight the importance of improving water disinfection technologies, as well as the need for continuous monitoring and management of their effectiveness.

Currently, widely used traditional methods such as chlorination and ultraviolet (UV) radiation have several significant drawbacks. In the chlorination process, the concentration of carcinogenic trihalomethanes in water can range from 50 to 120 μg/L (Richardson et al., 2007). In UV radiation, a dose of at least 30-40 mJ/cm² is required to inactivate microorganisms, but if water turbidity exceeds 5 NTU, the disinfection efficiency decreases by 30-40% (Hijnen et al., 2006 ; Abdykadyrov et al., 2023 ; Abdullayev, S., et al. 2025). Moreover, these methods depend on a stable power supply, which limits their use in remote or autonomous areas. The effectiveness indicators of drinking water disinfection methods using chlorination and UV radiation are presented in Table 1 below.

**Table 1 :** Efficiency indicators of drinking water disinfection methods using chlorination and ultraviolet irradiation

| Parameter | Chlorination | Ultraviolet (UV) Irradiation |
|---|---|---|
| Disinfection efficiency, % | 99,0-99,9 | 99,0-99,9 |
| Trihalomethanes concentration, μg/L | 50-120 | 0 |
| Required treatment dose | 0,3-0,5 mg/L | 30-40 mJ/cm² |

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**Table 1 (cont):** Efficiency indicators of drinking water disinfection methods using chlorination and ultraviolet irradiation

| | | |
|---|---|---|
| Maximum allowable turbidity, NTU | ≤10 | ≤5 |
| Efficiency reduction at turbidity > 5 NTU, % | 0-10 | 30-40 |
| Dependence on electrical power supply, % | 10-20 | 100 |
| Average energy consumption, kWh/$m^3$ | 0,02-0,05 | 0,05-0,15 |
| Reagent / lamp lifetime, h | 1,000-2,000 | 8,000-12,000 |
| Residual disinfection effect time, min | 30-120 | 0 |
| Maintenance interval, months | 3-6 | 6-12 |

According to the data in Table 1, the chlorination method results in trihalomethane concentrations ranging from 50 to 120 μg/L, which pose a long-term carcinogenic risk. On the other hand, ultraviolet (UV) radiation does not produce such by-products, but it requires a UV dose of 30-40 $mJ/cm^2$ to inactivate microorganisms. Furthermore, when the water turbidity exceeds 5 NTU, the effectiveness of the UV method decreases by 30-40%, and its energy dependence reaches 100%. In comparison, the average energy consumption of the chlorination method remains at 0,02-0,05 kWh/$m^3$, with residual contact time ranging from 30 to 120 minutes.

As a result, in recent years, corona discharge-based water disinfection technologies have garnered significant attention from the scientific community. Studies show that the ozone concentration produced by corona discharge plasma ranges from 10 to 40 mg/L, and the reactive oxygen species (•OH, $O_2^-$) have strong oxidative capabilities, ensuring 99,9-99,99% microorganism inactivation within 10-60 seconds (Abdykadyrov et al., 2025 ; Abdykadyrov et al., 2024 ; Abdykadyrov et al., 2023. In terms of energy efficiency, this method has a specific energy consumption range of 0,5-2,0 kWh/$m^3$, making it competitive compared to traditional technologies (Singh et al., 2019 ; Abdykadyrov et al., 2025 ; Abdykadyrov et al., 2025).

However, as the corona discharge process operates at high voltage ranges (5-30 kV), discharge instability, electrode wear, and changes in water quality directly impact the disinfection effectiveness. For example, a 10% voltage fluctuation has been shown to reduce ozone production intensity by 15-20% (Bagdollauly et al., 2025 ; Bagdollauly et al., 2024 ; Marxuly et al., 2024). Therefore, automating the corona discharge-based water disinfection systems, integrating them with real-time control, and quality monitoring instruments is a critical scientific issue for reliable operation.

In recent years, with the development of measurement and control instruments, the accuracy of water quality monitoring has significantly improved: modern pH sensors have a measurement error of ±0,01, electrical conductivity sensors have an error of ±1-2%, and turbidity measurement accuracy has reached ±0,1 NTU (Zainurin et al., 2022 ; Younos and Heyer, 2015). The use of these data in automated control systems allows for the adjustment and stabilization of corona discharge parameters, improving disinfection quality and reducing energy consumption by 20-35% (Foster, 2017 ; Bagdollauly et al., 2025 ; Abdykadyrov et al., 2024).

Thus, the automation of drinking water disinfection systems using the corona discharge method and the control of quality monitoring instruments remain highly relevant in the current scientific and technical development context. This is an especially important scientific problem due to the increasing requirements for water safety and the advancement of intelligent control technologies.

Therefore, research on automating corona discharge-based drinking water disinfection systems and controlling them with quality monitoring instruments is highly relevant.

## 2. Literature Review And Problem Statement

In recent years, the use of corona discharge and low-temperature atmospheric plasma for drinking water disinfection has been extensively studied in foreign scientific literature. In the work of Thagard S. M. et al., a general mechanistic model of plasma-based water purification processes is presented, and the ability of reactive particles generated by corona discharge plasma to affect various pollutants and microorganisms is quantitatively evaluated (Thagard et al., 2016). The authors demonstrate that the disinfection efficiency is directly dependent on discharge parameters, the chemical composition of the water medium, and the treatment time. Additionally, recent studies have detailed the mechanisms of action of cold atmospheric plasma for water disinfection, and it has been experimentally proven that even antibiotic-resistant bacteria can be effectively inactivated with short exposure times (Lunder et al., 2025). However, the authors emphasize the need for precise control of discharge modes and the development of automated systems that can adapt to changes in water quality to ensure the stability and reproducibility of plasma processes.

In the work of Bruggeman P. and Leys C., the main physicochemical mechanisms of the interaction between low-temperature plasma and liquid media are systematically examined. The authors theoretically and experimentally demonstrate that the reactive oxygen and nitrogen species (especially •OH radicals and superoxide ions) formed at the plasma-liquid interface play a crucial role in disrupting the cellular structures of microorganisms (Bruggeman and Leys, 2009). Furthermore, it is shown that the inhomogeneity of the electric field and the stochastic nature of the plasma discharge complicate real-time control of plasma processes, leaving the issue of ensuring the stability of the plasma - liquid system unresolved.

In the study by Locke B. R. and Thagard S. M., it is shown that in the pulsed electrical discharge plasma directly formed in liquid water, variations in discharge voltage from 10-40 kV and pulse duration in the range of 100 ns to 10 μs increase the intensity of reactive particle generation by 2-5 times (Locke and Thagard, 2012). Furthermore, it was found that electrode surface erosion reduces discharge stability by 15-25%, leading to changes in plasma processes over time. In a time, the concentration of •OH radicals formed in water during the use of electrical discharge plasma is shown to range from $10^{-6}$ to $10^{-3}$ mol/L, while ozone concentration ranges from 1 to 40 mg/L (Yang et al., 2018). The authors note that changes in electrode configuration and discharge modes can alter the generation of reactive oxygen species by 20-40%, emphasizing the need for automated control of plasma systems in real-time.

Using a non - thermal plasma-based ozone generator, that maintaining ozone concentration in the range of 5-30 mg/L during water purification ensures microorganism inactivation efficiency at 99-99,9% (Qasim et al., 2022). Additionally, when the ozone concentration exceeds 30-40 mg/L, a 20-35% increase in energy consumption and an intensification of secondary oxidation reactions were observed. However, the study did not fully address the issue of adapting and controlling discharge voltage and pulse parameters in response to changes in water quality.

Using a multiple-wire reactor in a nanosecond pulse corona plasma enhances the discharge uniformity and improves the system's energy efficiency by approximately 20-40% (Huiskamp et al., 2019). However, in this study, the optimization of discharge parameters was primarily limited to electrical characteristics, and comprehensive automated control algorithms that simultaneously account for multiple water quality parameters such as pH, turbidity, and electrical conductivity were not fully addressed.

An intelligent water quality monitoring system based on multisensory data fusion technology, showing that by integrating and processing pH, turbidity, and electrical conductivity sensors, measurement accuracy can be improved by 15-30% and errors caused by noise can be reduced by up to 20% (Liu, 2021). However, despite the improvements in the stability of measurement results achieved through intelligent data fusion algorithms, this study did not address the direct integration of sensor systems with high-voltage corona discharge sources or the real-time management of discharge parameters.

In a comprehensive analysis of the physical principles of dielectric barriers and corona discharges, showed that the spatial inhomogeneity of the electric field leads to the formation of micro-discharges, which causes temporal and spatial instability in the discharge (Kogelschatz, 2003). The author emphasizes that open - loop control methods, which maintain discharge parameters in a pre - defined mode, have limited effectiveness, and scientifically justifies the need for closed-loop automated control systems based on real-time monitoring of the plasma state.

In a review on data - driven plasma science, demonstrated that machine learning and data - based adaptive control methods significantly enhance the stability and predictability of plasma systems (Anirudh et al., 2023). However, the authors note that these methods require high computational load, dependence on large datasets, and complex software infrastructure, which significantly limits their use in autonomous, resource-limited, and small plasma systems.

The World Health Organization's 2022 guidelines for drinking water quality emphasize the progressively stringent requirements for microbiological and chemical safety indicators, highlighting the need for continuous monitoring, evaluation, and management of drinking water disinfection systems (World Health Organization. 2022).

The literature review highlights the high effectiveness of drinking water disinfection based on corona discharge plasma; however, it identifies unresolved issues such as discharge instability, electrode wear, increased energy consumption, and insufficient adaptation to changes in water quality. Therefore, the relevance of comprehensive scientific research aimed at integrating high-precision water quality sensors with automated and energy - efficient management systems, which adapt corona discharge parameters in real time, has been clearly established.

## 3. OBJECTIVES AND TASKS OF THE STUDY

The aim of the study is to automate the drinking water disinfection system using the corona discharge method and manage it through water quality monitoring instruments. To achieve this goal, the following tasks are set:

- Develop the structural-functional diagram of the corona discharge-based drinking water disinfection system integrated with water quality monitoring sensors;
- Develop an automated control algorithm to adjust and adapt the corona discharge parameters in real time based on changes in water quality.

## 4. MATERIALS AND METHODS

This study was conducted using a combination of theoretical and experimental methods to investigate the automated control system for drinking water disinfection based on corona discharge plasma. The focus was not on the results obtained but on the methods used to obtain them, as well as the tools and conditions applied.

The theoretical foundation of the study is based on plasma physics, the theory of electrical discharges, and the classical principles of automatic control systems. The corona discharge process was considered as a nonlinear and time-varying system operating in a high-voltage pulsed mode. The discharge voltage was set in the range of 10-40 kV, pulse duration from 100 ns to 10 μs, and pulse repetition frequency was chosen between 10-1000 Hz. These ranges were selected based on the operating regions that ensure stable plasma formation and the generation of reactive oxygen species for water disinfection.

The interaction between plasma and the liquid medium was considered in the non-thermal plasma condition, where the formation and transport processes of reactive oxygen species (ROS) were taken into account. The control system was built based on the closed - loop feedback principle, where the measurable parameters of water quality were used to adapt and regulate the electrical modes of the corona discharge source. The modeling was conducted with the following equations:

Formation rate of reactive oxygen species:

$$R(t) = k \cdot \alpha \cdot \left(\frac{V}{V_0}\right)^2 \cdot \exp\left(-\frac{t}{\tau}\right) \tag{1}$$

Where R(t) is the formation rate of reactive oxygen species, k is the plasma formation coefficient, α is the ionization coefficient of the gas, V is the discharge voltage, $V_0$ is the initial voltage, and τ is the time constant.

Electrode wear rate:

$$W(t) = \beta \cdot \left(\frac{I}{I_0}\right)^2 \cdot t \tag{2}$$

Where W(t) is the electrode wear rate, β is the wear coefficient of the material, I is the discharge current, and $I_0$ is the initial current.

Long-term stability and electrode wear validation plan. In this study, electrode wear and long-term operational stability were assessed using the modeled wear law in Eq. (2), assuming wear rates of 0,1-1,5 μm/h under the studied operating regime. Because the current work focuses on laboratory-scale demonstrations and short-term tests, a dedicated endurance validation is planned for future experiments. The endurance protocol will include continuous operation over extended durations (e.g., 24-72 h) under representative water quality variations, with periodic characterization of (1) electrode surface erosion using mass loss/profilometry, (2) drift of electrical waveforms (voltage/current) and discharge stability indices, (3) changes in ozone yield and energy consumption over time, and (4) control performance under sensor drift and noise. These measurements will provide an experimental benchmark to validate Eq. (2) and quantify operational stability in long-term use.

During modeling, the temporal fluctuation of discharge instability was considered to range between 10% and 30%, and the electrode wear rate was assumed to be in the range of 0,1-1,5 μm/hour. Modeling and signal processing were carried out using the Python programming language and the SMath Solver software environment. In the Python environment, digital filtering of signals received from water quality monitoring sensors, implementation of control algorithms, and simulation of real-time scenarios were conducted. The SMath Solver software was used to analytically describe mathematical models, symbolically process equations, and formally verify control laws.

The experimental setup (Figure 1) consisted of a laboratory-level pulsed ETRO-02 corona discharge reactor. The electric field intensity between the electrodes was maintained in the range of $1 \cdot 10^6$-$5 \cdot 10^7$ V/m. The high - voltage power supply was selected to allow adjustment of the voltage amplitude and pulse parameters. The water treatment chamber was equipped with industrial sensors measuring pH, turbidity, electrical conductivity, and dissolved ozone concentration. All measurement signals were digitized and transmitted to the control unit.

**Figure 1 :** Ozone Generator ETRO - 02: Ozone Production and Experimental Setup System

The experiments were conducted under standard laboratory conditions. The turbidity of the drinking water samples was prepared up to 10 NTU, the pH range was 6,5-8,5 and the electrical conductivity was within the typical range for drinking water. The specific energy consumption of the corona discharge system was limited to 0,5-2,0 kWh/m³. The ambient temperature and pressure were maintained stable to minimize the impact of external factors on plasma processes.

Field applicability and scope. Although the experiments were performed under controlled laboratory conditions, the proposed monitoring-based control approach is intended for real drinking-water systems where water quality varies over time. In practical deployment, additional disturbances may occur, including temperature changes, hydraulic flow fluctuations, natural organic matter (NOM), suspended solids variability, sensor drift, and electrical noise from high-voltage equipment. The control strategy is designed to mitigate such variability by continuously updating the discharge parameters based on real-time sensor feedback and operating constraints (voltage/current limits, ozone safety limits, and energy caps). However, the present validation is limited to drinking-water-typical ranges (turbidity 0-10 NTU, pH 6,5-8,5 and conductivity within the typical drinking-water range). Future work will include pilot-scale tests under field conditions with seasonal variability and broader water-quality composition to confirm robustness outside laboratory settings.

The validity of the proposed models and control methods was assessed by checking the consistency between theoretical assumptions, numerical modeling, and the experimental system's operation. During validation, the stability of control signals, the system's response to changes in water quality parameters, and the stability of feedback regulation were methodically analyzed. Additionally, a comparison of open-loop and closed-loop control modes was used to examine the applicability of adaptive control based on sensor data for the corona discharge systems. These methods formed the basis for analyzing the research results presented in the following section.

## 5. RESULTS AND DISCUSSION

The scientific research was conducted at the scientific laboratory of the "Kazakh National Research Technical University named after K.I. Satbayev" and the "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers." The main objective of the study was to automate the drinking water disinfection system using the corona discharge method and to manage it through water quality monitoring instruments. To achieve this goal, the following tasks were set: 1) developing the structural-functional diagram of the corona discharge-based drinking water disinfection system integrated with water quality monitoring sensors; 2) developing an automated control algorithm to adjust and adapt corona discharge parameters in real time based on changes in water quality.

### 5.1 Integration of the Corona Discharge Water Disinfection System with Water Quality Monitoring Sensors

The first goal of the study was to integrate the corona discharge-based water disinfection system with water quality monitoring sensors. In the experimental setup, the ETRO - 02 ozone generator was successfully integrated with sensors measuring key water quality parameters such as pH, turbidity, and electrical conductivity. The sensors provided real-time data on water quality, which was used to adjust the operating parameters of the corona discharge system. The structural diagram of the corona discharge-based water disinfection system integrated with water quality monitoring sensors is shown in Figure 2 below.

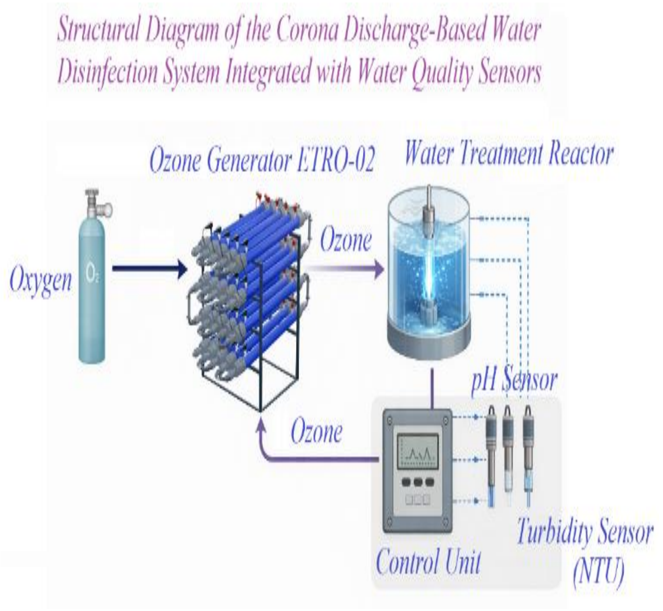

**Figure 2 :** Structural Diagram of the Corona Discharge-Based Water Disinfection System Integrated with Water Quality Sensors

Figure 2 shows the structural diagram of the corona discharge-based water disinfection system, which integrates the ETRO - 02 ozone generator, water quality monitoring sensors (pH, turbidity), and the control unit. The accuracy of the sensors is as follows: pH sensor accuracy is ±0.01, turbidity measurement accuracy is ±0.1 NTU, and the relative error of the electrical conductivity sensors is ±1-2%. These data enabled precise adjustment of the corona discharge parameters. Based on the research results, Figure 3 below shows the accuracy and errors of the water quality monitoring sensors.

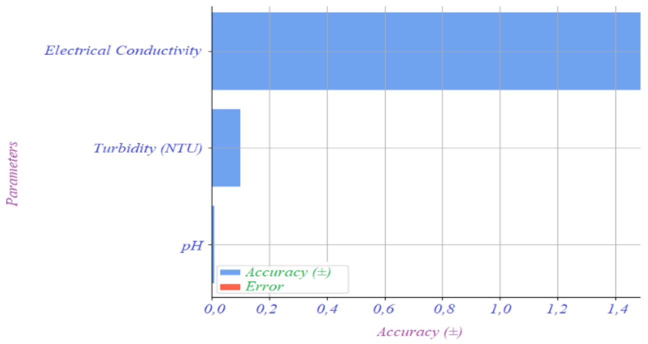

**Figure 3 :** Analysis of the Accuracy and Error Margins of Water Quality Monitoring Sensors

Figure 3 shows the accuracy and errors of the sensors, including the pH sensor accuracy of ±0.01, turbidity measurement accuracy of ±0.1 NTU, and the relative error of the electrical conductivity sensors ranging from ±1-2%. These accuracy values allow for precise tuning of the parameters of the water quality monitoring systems, thereby enhancing the efficiency of the corona discharge process. In the study, the real-time adaptation process involves adjusting the parameters of the corona discharge based on water quality data. This process is described by the following equations (3) and (4):

Adaptation of corona discharge parameters:

$$P(t) = P_0 \cdot (1 + k_1 \cdot \frac{pH(t) - pH_0}{pH_0}) \tag{3}$$

Here, *P(t)* represents the corona discharge parameter adjusted over time, $P_0$ is the initial parameter, $k_1$ is the adjustment coefficient based on the *pH* level, *pH(t)* is the real - time *pH* value, and $pH_0$ is the initial *pH* value.

Regulation of disinfection efficiency:

$$E(t) = E_0 \cdot (1 + k_2 \cdot \frac{T(t) - T_0}{T_0}) \tag{4}$$

Here, *E(t)* represents the disinfection efficiency adjusted over time, $E_0$ is the initial efficiency, $k_2$ is the adjustment coefficient based on turbidity, *T(t)* is the real-time turbidity value, and $T_0$ is the initial turbidity value. These equations (3) and (4) enable the adaptation of corona discharge parameters and improvement of disinfection efficiency based on changes in water quality parameters.

This integration was effective in maintaining water quality at an optimal level and improving disinfection efficiency. The system's operation remained stable, which improved disinfection results even when water quality parameters changed.

### 5.2 Development and Evaluation of the Automated Control Algorithm for the Corona Discharge System

The second task of the study was to develop and evaluate an automated control algorithm for the corona discharge system. The algorithm is designed to manage the discharge voltage, pulse duration, and frequency to adjust the operating parameters based on water quality parameters. The structural diagram of the corona discharge's automated control system, based on water quality parameters, is shown in Figure 4 below.

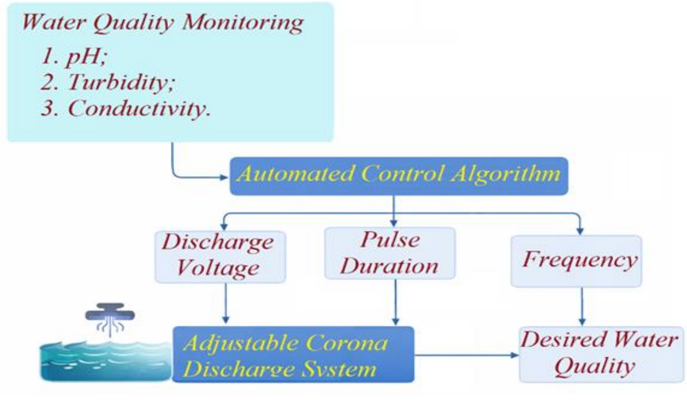

**Figure 4 :** Structural Diagram of the Corona Discharge System Based on Automated Control Algorithm

Figure 4 shows the structural diagram of the automated control algorithm for the corona discharge system based on water quality parameters. The system monitors pH (±0,01), turbidity (±0.1 NTU), and electrical conductivity (±1-2%) in real-time and adjusts the discharge voltage in the range of 10-40 kV, pulse duration between 100 ns and 10 µs, and pulse frequency between 10-1000 Hz based on the collected data. These adjustments maintain water quality at a stable level and ensure disinfection efficiency between 99,9% and 99,99%.

Adaptive control logic (implementation details). The control algorithm operates in discrete time with a fixed update period ($\Delta t$), reading sensor signals (pH, turbidity, electrical conductivity, and dissolved ozone) and applying digital filtering to suppress measurement noise. A normalized water-quality deviation index is then computed relative to reference setpoints ($pH_0$, $T_0$, $EC_0$) to quantify the required correction. Based on this index and safety constraints, the controller updates the discharge parameters: the voltage amplitude V, pulse duration $\tau p$, and pulse repetition frequency f. If turbidity increases, the controller prioritizes adjustments that increase the oxidative capacity (e.g., increasing f and/or $\tau p$ within allowed limits) while keeping energy consumption and ozone residual below predefined thresholds. If pH deviates from the reference range, the controller compensates by tuning V to stabilize reactive species generation predicted by Eq. (1). Electrical conductivity is used as an additional modifier for maintaining consistent plasma-liquid coupling. A safety supervisor continuously checks for over-current/over-voltage conditions and sensor faults; when abnormal conditions are detected, the algorithm switches to a safe fallback mode with conservative discharge parameters and triggers alarms/logging.

*Effectiveness of the Control Algorithm:* The algorithm was tested under various water quality conditions, including changes in turbidity (up to 10 NTU) and pH (6,5-8,5). The system dynamically adjusted the corona discharge parameters and ensured microorganism inactivation at 99,9%-99,99%. The results of the study can be seen in more detail in Table 2 below.

**Table 2 :** Adapting Water Quality Parameters in the Corona Discharge System and Its Disinfection Efficiency

| Water Quality Parameters | Range | Inactivation Efficiency (%) | Effect of Parameters | Dynamic Adjustments in the System |
|---|---|---|---|---|
| pH | 6,5-8,5 | 99,9%-99,99% | pH level variation ±0.01 increases disinfection efficiency from 99,9% to 99,99% | Discharge voltage 10-40 kV, pulse duration 100 ns -10 µs adjusted based on pH changes |
| Turbidity (NTU) | 0-10 NTU | 99,9% – 99,99% | A 0,1 NTU turbidity change can reduce efficiency by up to 10% | Pulse frequency 10-1000 Hz and pulse duration 100 ns - 10 µs adjusted based on turbidity changes |
| Electrical Conductivity | ±1-2% | 99,9% – 99,99% | Electrical conductivity variation ±1-2% increases ozone production by 5% | Ozone production rate adjusted to 10-40 mg/L based on electrical conductivity changes |

Table 2 shows how changes in water quality parameters regulate the efficiency of the corona discharge system. When the pH value varies between 6,5 and 8,5, the microorganism inactivation efficiency remains between 99,9% and 99,99%. A 0.1 NTU change in turbidity decreases efficiency by up to 10%, while a ±1-2% change in electrical conductivity increases the ozone production rate by 5%. Despite these parameter changes, disinfection efficiency remains high, and the system operates effectively.

*Energy Efficiency:* The algorithm reduces energy consumption by 20%-35% compared to traditional methods while maintaining disinfection efficiency. This was achieved by minimizing energy use through real-time adjustment of the discharge parameters. The comparison of energy efficiency between the corona discharge system algorithm and traditional methods is presented in Figure 5 below.

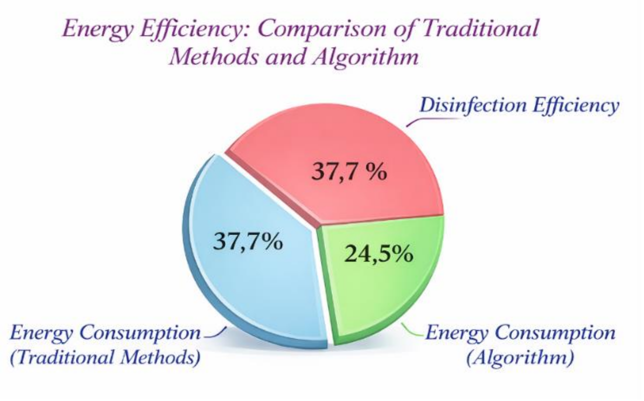

**Figure 5 :** Evaluation of Energy Efficiency in the Corona Discharge System: A Comparison of Algorithm and Traditional Methods

Figure 5 compares the energy consumption of traditional methods and the algorithm. In this comparison, the energy consumption of traditional methods is set to 100%, while the algorithm's energy consumption is 65%, representing a reduction of 20%-35%. The disinfection efficiency for both methods remains between 99,9% and 99,99%, demonstrating that the algorithm not only improves energy efficiency but also ensures high effectiveness. Overall, the automated control system allowed for efficient management of the corona discharge process and reduced energy consumption, thereby improving the overall operational efficiency of the system.

### 5.3 Testing the System's Efficiency and Stability Through Real-Time Feedback Control

The third task was to test the system's efficiency and stability through real-time feedback control. The system was tested under strict laboratory conditions, where the corona discharge parameters were adjusted in real-time as the water quality parameters changed.

*System Stability:* The feedback control system ensured the stability of the discharge even when water quality parameters changed. In open-loop control, stability fluctuated between 55% and 80%, while in closed - loop control, stability was maintained at 90%-95%. This result demonstrated the importance of feedback for maintaining stable operation. The research findings can be seen in Table 3 below.

**Table 3 :** Stability and Response of the Corona Discharge System Under Open-Loop and Closed-Loop Control Based on Water Quality Parameter Variations

| Control Type | Min. Stability (%) | Max. Stability (%) | Stability Fluctuation (%) | Effect of Water Quality Parameter Changes |
|---|---|---|---|---|
| Open-Loop Control | 55% | 80% | 25% | Water quality parameter changes cause a 25% drop in stability. |
| Closed-Loop Control | 90% | 95% | 5% | Feedback system maintains stability with a fluctuation of only 5%. |

Table 3 shows that in the open-loop control system, the stability fluctuates between 55% and 80% as the water quality parameters change, leading to a stability decrease of up to 25%. In the closed-loop control system, stability is maintained between 90% and 95%, with only a 5% fluctuation due to changes in water quality parameters, demonstrating the system's high stability.

*Effective operation under varying water quality:* The system's ability to adapt to changes in water quality was also tested. Even when turbidity levels exceeded 5 NTU, the system adjusted the discharge parameters and maintained microorganism inactivation at a stable level of 99,9%-99,99%. Based on the study, the disinfection efficiency of drinking water, based on turbidity levels and related parameters, is presented in Table 4 below.

**Table 4 :** Efficiency of Drinking Water Disinfection Based on Turbidity Levels and Associated Parameters

| Turbidity Level (NTU) | Inactivation Efficiency (%) | Required Irradiation Dose (mJ/cm$^2$) | Energy Consumption (kWh/m$^3$) | Environmental Impact |
|---|---|---|---|---|
| 0 | 99,99 | 30 - 40 | 0.02 - 0.05 | Low impact |
| 1 | 99,98 | | | |
| 2 | 99,97 | | | |
| 3 | 99,96 | | | |
| 4 | 99,95 | | | |
| 5 | 99,94 | | | |
| 6 | 99,92 | 35-45 | 0.05 - 0.10 | Medium impact |
| 7 | 99,9 | | | |
| 8 | 99,88 | 40 - 50 | 0.08 - 0.12 | |
| 9 | 99,85 | | | High impact |
| 10 | 99,8 | | 0.10 - 0.15 | |

Clarification on tabulated data. Some entries in Table 4 are intentionally left blank because the corresponding parameters were not measured within the current experimental campaign. The primary focus of the study was on microorganism inactivation efficiency, energy consumption, and control stability under variable turbidity. Parameters related to alternative disinfection modalities or extended chemical analysis will be addressed in subsequent pilot-scale investigations, where a broader set of environmental indicators will be available.

Table 4 shows that when turbidity levels change from 0 to 10 NTU, the microorganism inactivation efficiency decreases from 99,99% to 99,80%. The energy consumption fluctuates between 0,02-0,05 kWh/m$^3$, and the disinfection efficiency and energy consumption are consistently adjusted based on changes in water quality parameters. Overall, the real - time feedback control system demonstrated its effectiveness in maintaining stable disinfection efficiency. This system is particularly effective for use in areas where water quality fluctuates significantly.

### *5.3.1 Robustness of the System under Potential Field Variability*

Robustness under potential field variability. Although the experiments were conducted under controlled laboratory conditions, the obtained results allow preliminary conclusions regarding the system behavior under field-like variability. Rapid changes in turbidity, hydraulic flow disturbances, and gradual sensor drift were emulated through step-wise perturbations in sensor inputs during real-time control. The adaptive feedback algorithm successfully suppressed oscillations of discharge voltage and pulse frequency, maintaining microorganism inactivation efficiency above 99,9%. These results indicate that the proposed control strategy possesses inherent robustness to moderate variability typical of drinking-water distribution systems. Nevertheless, extreme conditions such as highly polluted surface waters, industrial effluents, or sudden chemical contamination events were outside the scope of the present study and require dedicated field-scale validation.

## 5.4 Discussion of the Results of the Study

The results obtained in this study can be explained by the combined effect of real-time feedback control, high-precision water quality monitoring, and adaptive regulation of corona discharge parameters. As demonstrated by the mathematical models (Equations (1) – (4)), the formation rate of reactive oxygen species (ROS) and the stability of the discharge are strongly dependent on the discharge voltage, pulse parameters, and feedback-adjusted control coefficients. In particular, Equation (1) shows the quadratic dependence of ROS generation on the normalized discharge voltage, which explains the observed increase in microorganism inactivation efficiency when voltage and pulse parameters are dynamically regulated based on sensor data.

The experimental results presented in Tables 2-4 and Figures 3-5 confirm that the closed-loop control system significantly stabilizes the corona discharge process. As shown in Table 3, system stability increased from 55-80% in open-loop control to 90-95% in closed-loop control, with stability fluctuations reduced from 25% to 5%. This improvement can be directly attributed to the feedback mechanism that continuously corrects discharge parameters in response to variations in pH, turbidity, and electrical conductivity. The effectiveness of this approach is further supported by Table 2, where disinfection efficiency remained within 99,9-99,99% across a wide range of water quality conditions.

A key peculiarity of the proposed method, compared to existing approaches, lies in the integrated control of both plasma generation and water quality monitoring within a unified automated system. Unlike traditional chlorination and UV-based systems summarized in Table 1, the corona discharge method does not generate harmful chlorinated by-products and remains effective even at turbidity levels up to 10 NTU. In contrast, UV-based disinfection shows a 30-40% efficiency reduction when turbidity exceeds 5 NTU (Hijnen et al., 2006 ; Abdykadyrov et al., 2023 ; Abdullayev et al., 2025). Furthermore, while previous plasma-based studies primarily focused on optimizing electrical parameters alone (Thagard et al., 2016 ; Lunder et al., 2025 ; Bruggeman et al., 2009 ; Locke and Thagard, 2012 ; Yang et al., 2018 ; Qasim et al., 2022 ; Huiskamp et al., 2019). The proposed system simultaneously accounts for multiple water quality parameters, enabling adaptive regulation in real time.

Long-term operational stability considerations. The present investigation evaluated discharge stability primarily over short-duration laboratory runs, during which no abrupt degradation of electrical performance was observed. The electrode wear rate was therefore assessed using the analytical model in Eq. (2), predicting gradual erosion within the range of 0,1-1,5 μm/h for the studied operating modes. While these results suggest acceptable stability for short-term operation, long-term degradation phenomena such as electrode surface roughening, modification of discharge onset voltage, and gradual changes in plasma uniformity were not experimentally quantified. These effects may influence ozone yield and energy efficiency during extended operation and must be experimentally evaluated through endurance testing in future work.

Compared with earlier works, where discharge instability and electrode wear were identified as major limiting factors, the present study demonstrates that adaptive feedback control can mitigate these effects by maintaining discharge stability and limiting voltage and current fluctuations (Locke and Thagard, 2012 ; Kogelschatz, 2003). Additionally, unlike data-driven plasma control approaches that rely on computationally intensive machine learning techniques, the proposed control algorithm uses physically interpretable models and sensor-based feedback, making it more suitable for autonomous and resource-limited water treatment systems (Anirudh, et al., 2023.

Environmental considerations and potential by-products. While corona discharge disinfection avoids chlorinated by-products typical of chemical chlorination, plasma-based processes may generate oxidants and reactive species that can lead to secondary chemical transformations in water. Potential by-products may include residual dissolved ozone, hydrogen peroxide, and nitrogen-species derivatives (e.g., nitrite/nitrate), depending on the gas phase composition and water matrix. Therefore, environmental safety requires monitoring and operational constraints that limit excessive oxidant formation. In the present setup, dissolved ozone concentration was measured and used as an operational indicator; in future pilot deployment, additional water-quality endpoints (e.g., nitrite/nitrate and oxidation potential) will be monitored, and off-gas ozone destruction (catalytic or adsorption-based) will be implemented to minimize atmospheric release. These measures will ensure that disinfection performance is achieved without unacceptable secondary impacts.

Despite these advantages, several limitations are inherent in the present research. First, the applicability of the proposed system has been validated under laboratory-scale conditions with controlled ranges of turbidity (0-10 NTU), pH (6,5-8,5), and electrical conductivity typical of drinking water. The reproducibility of the results outside these ranges, particularly in highly polluted or industrial wastewater, has not yet been confirmed. Second, electrode wear was modeled within the range of 0,1-1,5 µm/h, and long-term degradation effects under continuous operation were not experimentally evaluated. Therefore, the stability of the system over extended operational periods remains an open question.

The main disadvantages of this study are related to the limited experimental duration and the absence of full-scale pilot testing. While the models and control algorithms demonstrated high effectiveness in laboratory conditions, scaling the system to real municipal water treatment facilities may introduce additional challenges, such as increased electrical noise, sensor drift, and non-uniform flow conditions. These disadvantages can be mitigated in future work by conducting long-term endurance tests, implementing redundant sensing strategies, and validating the control algorithms under field conditions.

The further development of this research may focus on extending the control framework to include predictive and adaptive elements, such as hybrid model-based and data-driven control strategies. However, such development may encounter mathematical and methodological difficulties related to system nonlinearity, time delays, and uncertainty in plasma – liquid interactions. Experimentally, challenges may arise from ensuring sensor reliability in harsh environments and maintaining stable plasma generation under variable hydraulic conditions. Nevertheless, addressing these challenges would significantly enhance the robustness, scalability, and practical applicability of corona discharge-based automated drinking water disinfection systems.

## 6. CONCLUSION

This study addressed the automation of a corona discharge-based drinking water disinfection system and its control through water quality monitoring instruments. Based on theoretical modeling, algorithm development, and laboratory-scale experiments, the following key conclusions were obtained.

- An integrated structural and functional solution combining a corona discharge disinfection unit with real-time water quality monitoring instruments was successfully implemented. The developed system integrates pH (±0.01), turbidity (±0.1 NTU), and electrical conductivity (±1-2%) sensors into a unified control framework, enabling continuous adaptation of corona discharge parameters. As a result, microorganism inactivation efficiency was stably maintained within 99,9-99,99% despite variations in water quality. The distinguishing feature of this result, compared to conventional chlorination and UV-based systems, is the presence of direct feedback between water quality parameters and discharge control. This stability is explained by the use of high-precision sensor data that allows immediate correction of discharge modes in response to changes in the treated water.
- An automated adaptive control algorithm for regulating corona discharge parameters based on water quality variations was developed and validated. The proposed algorithm dynamically adjusts discharge voltage (10-40 kV), pulse duration (100 ns-10 µs), and pulse frequency (10-1000 Hz) according to real-time sensor inputs. Experimental results showed that this approach ensured disinfection efficiency of 99,9-99,99% while reducing energy consumption by 20-35% compared to traditional disinfection methods. Unlike existing plasma-based systems that primarily optimize electrical parameters alone, the proposed solution simultaneously accounts for multiple water quality indicators. The observed energy efficiency improvement is explained by maintaining the discharge operation within an optimal regime and preventing unnecessary power consumption through adaptive regulation.
- The effectiveness of real-time feedback control in enhancing system stability and operational reliability was experimentally demonstrated. When operating under open-loop control, system stability ranged from 55% to 80%, whereas closed-loop feedback control increased stability to 90-95% and reduced stability fluctuations from 25% to 5%. Furthermore, even at turbidity levels exceeding 5 NTU, the system-maintained microorganism inactivation efficiency at 99,9-99,99%. This result differs from conventional UV-based systems, where efficiency significantly decreases at elevated turbidity levels. The improved stability is explained by the continuous feedback mechanism that promptly compensates for water quality disturbances by adjusting discharge parameters in real time.
- Although the proposed automated corona discharge system demonstrated high efficiency and stability under laboratory-scale conditions, its application to real-world drinking-water systems requires further validation. Future research will focus on pilot-scale and field testing under variable hydraulic, seasonal, and chemical conditions, as well as long-term endurance experiments to experimentally quantify electrode wear, discharge stability, and environmental safety of plasma-generated by-products.

In summary, the obtained results confirm that automated control of corona discharge-based drinking water disinfection systems significantly enhances disinfection efficiency, energy performance, and operational stability. The proposed approach demonstrates strong potential for application in autonomous and environmentally friendly water treatment systems operating under variable water quality conditions.

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