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RESEARCH ARTICLE

INTELLIGENT CONTROLLED CORONA DISCHARGE WATER DISINFECTION SYSTEM POWERED BY RENEWABLE ENERGY SOURCES

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ABSTRACT

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This paper presents the development and substantiation of an intelligent control approach for a corona discharge – based water disinfection system powered by renewable energy sources. The aim of the study is to improve disinfection efficiency and energy performance of the system under conditions of unstable power supply by optimizing the operating regimes of the corona discharge. The research combines theoretical analysis, mathematical modeling, machine learning and reinforcement learning methods, and laboratory-scale experiments. The results show that stable corona discharge operation in the voltage range of 5 – 30 kV ensures the generation of ozone at concentrations of 10 – 40 mg/L and hydroxyl radicals in the range of 10^{-9} – 10^{-6} mol/L, providing microorganism inactivation efficiencies of 90 – 99.99%. The application of the intelligent control algorithm enables discharge instability to be maintained within ± 10 – 15% under solar and wind energy fluctuations of ± 20 – 50%, while reducing overall energy consumption by 15 – 35%. The obtained results demonstrate that the proposed approach has significant scientific and practical potential for enhancing the stability and energy efficiency of renewable energy-powered water disinfection systems.

KEYWORDS

Corona discharge, water disinfection, renewable energy sources, intelligent control, machine learning, plasma technologies.

1. INTRODUCTION

Ensuring the microbiological safety of drinking water is one of the key scientific challenges in modern applied physics, chemical technology, and environmental engineering. According to the World Health Organization, more than 2.2 billion people worldwide use drinking water that does not meet sanitary standards, and waterborne diseases cause approximately 485,000 deaths annually (World Health Organization, 2023). These facts indicate that the improvement of water disinfection technologies remains highly relevant.

Although conventional chlorination and ultraviolet (UV) irradiation methods are widely used, they have significant limitations. During chlorination, the concentration of trihalomethanes can reach 50–120 µg/L, posing carcinogenic risks (Richardson et al., 2007). UV-based methods require an irradiation dose of 30–40 mJ/cm² to achieve effective microbial inactivation; however, their efficiency decreases in highly turbid water and they require a stable energy supply (Abdullayev et al., 2025; Abdykadyrov et al., 2023). In recent years, corona discharge-based water disinfection technologies have emerged as a promising alternative.

Under high-voltage conditions of 5–30 kV, corona discharge generates low-temperature plasma, leading to the formation of strong oxidizing agents such as ozone (O₃), hydroxyl radicals (•OH), and atomic oxygen (Abdykadyrov et al., 2023; Abdykadyrov et al., 2025). These active species damage the cellular structures of microorganisms, enabling 99.9–99.99% inactivation within 10–60 seconds, with an energy consumption of 0.5–2.0 kWh/m³ (Abdykadyrov et al., 2025; Abdykadyrov et al., 2024).

At the same time, the efficiency of water disinfection systems is directly dependent on energy availability. According to the International Energy Agency, approximately 770 million people worldwide lack access to reliable electricity, and 30–40% of water treatment facilities do not operate at full capacity due to energy shortages (Dechamps, 2023; Abdykadyrov et al., 2024). In this context, the use of renewable energy sources such as solar and wind power is of significant scientific and practical importance.

However, integrating corona discharge disinfection systems with renewable energy sources complicates control due to energy intermittency, high-voltage operating modes, and variable water quality parameters.

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As reported in the literature, the application of intelligent control algorithms can reduce energy consumption by 15–35% while improving system stability (Abdykadyrov et al., 2025; Abdykadyrov et al., 2025). Nevertheless, comprehensive studies of such approaches in water disinfection systems that combine corona discharge technology with renewable energy sources remain insufficient. Overall, Figure 1 presents the process flow diagram of a corona discharge water disinfection system powered by renewable energy sources.

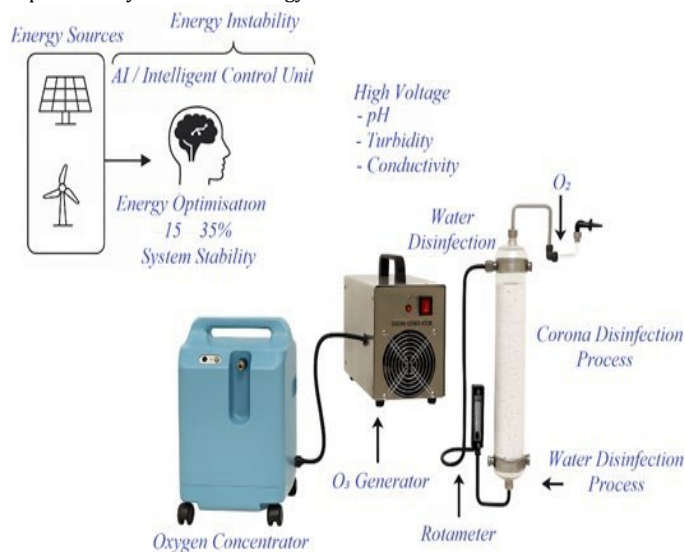


Figure 1: Conceptual architecture of an AI-controlled corona discharge water disinfection system powered by renewable energy sources

In Figure 1, an AI-based intelligent control unit integrated with renewable energy sources is shown to compensate for energy instability and optimize the operating modes of a corona discharge water disinfection system. By monitoring high-voltage conditions and key water quality parameters (pH, turbidity, and conductivity), the proposed architecture reduces energy consumption by 15–35% while ensuring stable and efficient disinfection performance.

In this regard, investigating the intelligent control of a corona discharge water disinfection system powered by renewable energy sources represents a relevant and important scientific research direction.

2. LITERATURE REVIEW AND PROBLEM STATEMENT

In recent years, the effectiveness of plasma- and corona-discharge-based technologies for water disinfection has been quantitatively demonstrated. The use of pulsed corona discharge plasma enables virus inactivation levels of 99.9 – 99.99% in water, with complete inactivation achieved within 10 – 60 s (Song et al., 2022). According to their results, the main contributing factors are ozone (O_3 , 10 – 40 mg/L), hydroxyl radicals ($\bullet OH$), and reactive oxygen species, which directly damage viral capsids and RNA/DNA structures. The mechanisms of virus inactivation by low-temperature atmospheric plasma, found that plasma treatment leads to oxidation of protein bonds by 30 – 60% and degradation of genetic material by more than 70% (Lan et al., 2024). In addition, it was shown that the inactivation efficiency of plasma significantly increases when the electric field strength is in the range of 5 – 25 kV. However, the issue of optimizing the system's energy consumption was not addressed in that study. The use of bubble-assisted corona discharge for drinking water treatment can reduce the concentration of disinfection by-products by 40 – 65% (Gao et al., 2023). Moreover, the specific energy consumption of plasma treatment was reported to be in the range of 0.6 – 1.8 kWh/m³. Nevertheless, this study did not consider the adaptation of the corona discharge system to variable operating modes and the instability of energy sources. Thus, the reviewed works quantitatively confirm that corona discharge plasma can effectively inactivate viruses and microorganisms in water while reducing additional chemical risks. However, the dynamic nature of energy consumption and the application of intelligent control approaches remain insufficiently addressed in the existing literature.

The virus inactivation mechanism in water using corona discharge plasma is based on the generation of highly reactive chemical species under high-voltage electrical conditions. When a corona discharge is applied at voltages in the range of 5–25 kV, various oxidizing agents are produced directly in the water phase, including ozone (O_3), hydroxyl radicals ($\bullet OH$), and a wide spectrum of reactive oxygen species (ROS).

These reactive species interact with viral particles, causing oxidative damage to viral capsid proteins and leading to the degradation of viral RNA or DNA structures. The combined action of ozone, hydroxyl radicals, and other ROS results in the rapid loss of viral infectivity. Due to the strong oxidative potential of these species, virus inactivation efficiencies as high as 99.9–99.99% can be achieved within a relatively short treatment time.

Despite the high effectiveness of corona discharge plasma for water disinfection, several challenges remain. In particular, further optimization of energy consumption and the development of intelligent control strategies are required to enhance system efficiency and ensure stable, scalable operation for practical water treatment applications. The optical and chemical characteristics of solvated electrons generated at a water cathode under plasma electrolysis conditions and demonstrated that plasma discharge parameters have a direct influence on the kinetics of reactive species formation (Martin et al., 2024). The disinfection efficiency of microorganisms using electrohydraulic discharge plasma depends on discharge energy, pulsed operating regimes, and treatment time, thereby characterizing the kinetic behavior of plasma-based water treatment processes (Suwannarat et al., 2024). However, the models and experimental systems proposed in these studies are mainly based on operation under a fixed power supply, while adaptation to variable regimes of renewable energy sources and the implementation of intelligent energy management have not been sufficiently addressed.

The performance of decentralized, solar-powered water treatment systems for industrial wastewater treatment and drinking water supply, demonstrating the environmental and operational advantages of renewable energy sources (Hafeez et al., 2021). A solar-powered drinking water ozonation system in Western Kenya, found that daily and seasonal fluctuations in solar radiation have a direct impact on the stability of ozone generation and disinfection efficiency (Hendrickson et al., 2020). However, the control strategies employed in these studies were mainly based on simple threshold or predefined logic, and issues related to dynamic energy flow optimization and the implementation of intelligent control algorithms were not sufficiently addressed, resulting in limited overall energy efficiency of the systems.

Overall, the performance characteristics of solar-powered water treatment and ozonation systems can be described through their response to variations in solar radiation, system stability, disinfection efficiency, ozone generation, control complexity, and energy efficiency. Under conditions where solar radiation fluctuates within a range of approximately ± 20 –50%, the stability of the system typically varies by about ± 15 –35%. Despite these variations, disinfection efficiency remains relatively high, generally within the range of 85–99%.

At the same time, ozone generation in such systems is subject to significant fluctuations, commonly ranging from ± 25 –55%, which directly affects the consistency of the treatment process. The control strategies applied in these systems are usually based on simple predefined or threshold-based logic, corresponding to a low level of control algorithm complexity. While these approaches are easy to implement, they limit the system's ability to adapt to rapidly changing operating conditions.

As a result of these constraints, the overall energy efficiency of solar-powered water treatment and ozonation systems is typically limited to about 55–75%. This analysis indicates that the use of simple control algorithms reduces operational flexibility and highlights the need for more advanced and adaptive control strategies to improve stability, efficiency, and reliability under variable solar irradiation conditions.

Hybrid renewable energy systems based on solar and wind power for wastewater treatment plants from a multi - objective optimization perspective, showing that time-varying energy demand significantly complicates stable system operation (Nguyen et al., 2020). On the application of hybrid energy systems in wastewater treatment and bioenergy production, noting that the instability of energy sources leads to reduced efficiency of technological processes and lower treatment quality (Tee et al., 2016). The application of hybrid renewable energy systems in desalination and water treatment, demonstrated that in the absence of real-time adaptive control mechanisms, energy imbalance disrupts process stability and limits overall system efficiency (Esmailion, 2020). Overall, Figure 2 presents a conceptual diagram highlighting the energy imbalance and research gaps of a solar-wind hybrid renewable energy system for desalination and wastewater treatment.

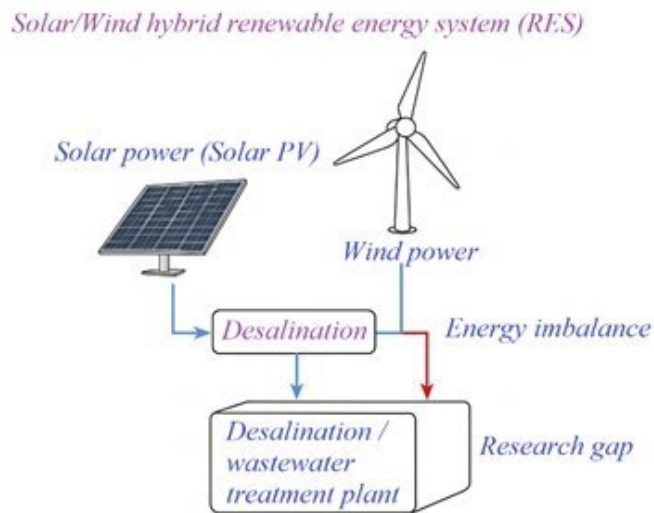


Figure 2: Conceptual diagram of a hybrid solar – wind renewable energy system for desalination and wastewater treatment highlighting energy imbalance and research gaps

The figure illustrates a hybrid solar-wind renewable energy system supplying desalination and wastewater treatment units, where time-varying energy demand and generation lead to energy imbalance. It also highlights that the absence of real-time adaptive control mechanisms reduces process stability and limits the overall energy efficiency of the system.

The use of machine learning methods for energy consumption prediction and management in wastewater treatment plants, demonstrating that intelligent models can significantly contribute to more efficient energy utilization (Alali et al., 2023). Proposed machine learning – based energy consumption models for water treatment facilities and showed that optimization of technological parameters can lead to a substantial reduction in energy use (Zhang et al., 2021). In addition, applying machine learning algorithms to a photovoltaic electro - Fenton wastewater treatment system can improve energy efficiency and reduce energy consumption by 20 – 30% (Zhang et al., 2025). However, these studies mainly focus on conventional electrochemical, membrane, or electro-Fenton systems, while the application of intelligent control methods to corona discharge plasma – based water disinfection systems remains insufficiently investigated. Overall, Table 1 presents a comparison of energy efficiency indicators in machine learning – based water treatment systems.

Table 1: Comparison of energy efficiency indicators in machine learning-based water treatment systems

No	Year	Energy Consumption Reduction	Prediction Accuracy (R^2)	Number of ML Models Used	Control Adaptability Level	Compatibility with Corona Discharge
1	2021	15 – 25 %	0.85 – 0.92	2 – 3	1	-
2	2023	18 – 30 %	0.88 – 0.95	3 – 4	1	-
3	2025	20 – 30 %	0.90 – 0.97	4 – 5	2	-

The table compares the energy efficiency indicators of machine learning-based water treatment systems, showing that energy consumption can be reduced by 15 – 30% with prediction accuracy (R^2) reaching 0.85 – 0.97. It also indicates that, despite improved control adaptability, none of the reviewed approaches have been applied to corona discharge plasma systems, highlighting a clear research gap.

Real-time power control methods for high-voltage power supplies used in dielectric barrier discharge (DBD) reactors, demonstrating that discharge stability is strongly coupled with the thermal characteristics of the load (Neretti et al., 2022). This relationship can be expressed through the average discharge power,

$$P(t) = \frac{1}{T} \int_0^T V(t)I(t)dt \quad (1)$$

where $V(t)$ and $I(t)$ denote the instantaneous voltage and current, respectively, and T is the pulse period.

The thermal stability of the discharge is governed by the energy balance of the plasma reactor, which can be described as,

$$C \frac{dT}{dt} = P(t) - h(T - T_{env}) \quad (2)$$

where C is the thermal capacity of the system, h is the heat transfer coefficient, and T_{env} is the ambient temperature.

Furthermore, (Pan et al., 2023) showed that deep learning – based models for pulsed discharge plasma catalysis significantly improve the prediction accuracy of discharge parameters, with the control input generally formulated as,

$$u(t) = f_{NN}(V(t), I(t), T(t)) \quad (3)$$

where f_{NN} represents a neural network model. However, these control strategies are mainly developed for fixed or predefined power operation, and the intermittent and highly variable supply conditions inherent to renewable energy sources are not sufficiently incorporated into the above formulations.

A comprehensive analysis of the relationship between key water quality parameters – pH, turbidity, and electrical conductivity – and the efficiency

of plasma treatment using a water surface plasma source based on volume dielectric barrier discharge (Yang et al., 2022). Although the study demonstrated that variations in these parameters significantly influence discharge characteristics and treatment performance, an intelligent control architecture capable of automatically regulating water quality parameters in real time was not proposed.

The performance of plasma-based water treatment is strongly influenced by key water quality parameters, including pH level, turbidity, and electrical conductivity. Under mildly acidic to neutral conditions, with pH values in the range of 5.0–7.0, low turbidity levels between 0 and 10 NTU, and electrical conductivity of 200–500 $\mu\text{S}/\text{cm}$, the plasma discharge remains relatively stable, with stability variations of approximately ± 10 –15%. In this case, treatment efficiency is high and typically ranges from 90% to 98%.

As water conditions shift toward slightly alkaline environments, with pH values of 7.0–9.0, increased turbidity of 10–30 NTU, and higher electrical conductivity in the range of 500–1200 $\mu\text{S}/\text{cm}$, plasma discharge stability decreases. Stability fluctuations increase to about ± 20 –30%, resulting in a moderate reduction in treatment efficiency to approximately 80–90%.

Under strongly alkaline conditions, characterized by pH values of 9.0–11.0, high turbidity levels of 30–60 NTU, and elevated electrical conductivity of 1200–2500 $\mu\text{S}/\text{cm}$, plasma discharge stability is significantly affected. Variations in discharge stability can reach ± 30 –45%, leading to a notable decline in treatment efficiency, which typically falls within the range of 65–80%.

Overall, these observations demonstrate that changes in water quality parameters can substantially impact plasma discharge behavior and treatment effectiveness, with efficiency varying from about 65% to 98%. Despite this strong dependence, none of the examined operating conditions incorporate real-time intelligent control. This clearly indicates the necessity for adaptive and intelligent control strategies capable of dynamically responding to variations in water quality to ensure stable operation and consistently high treatment performance.

The reviewed studies confirm the high effectiveness of corona discharge plasma for water disinfection and the strong potential of renewable energy sources. However, challenges related to the intermittent nature of renewable energy supply, the complexity of energy optimization in high-

voltage systems, and the lack of intelligent control algorithms accounting for variable water quality parameters remain unresolved.

The current state of applying artificial intelligence techniques to optimize renewable energy systems, demonstrating the potential of intelligent algorithms for managing energy flows, improving system stability, and enhancing overall efficiency (Ukoba et al., 2024). AI-based efficiency analysis techniques for photovoltaic renewable energy systems, showing that control performance can be significantly improved under complex and variable operating conditions (Alam et al., 2023). In addition, intelligent energy management strategies for electrical power systems, highlighting the importance of adaptive control approaches for high-voltage equipment (Sechilariu, 2020). However, these studies primarily focus on general energy systems and electrical installations, while comprehensive investigations integrating corona discharge – based water disinfection systems with renewable energy sources using artificial intelligence remain insufficiently explored.

All of the above considerations indicate that investigating the intelligent control of a corona discharge water disinfection system powered by renewable energy sources is scientifically and practically relevant, and they substantiate the necessity of conducting comprehensive research in this direction.

3. THE AIM AND OBJECTIVES OF THE STUDY

The aim of the study is to develop and substantiate an intelligent control approach for a corona discharge – based water disinfection system powered by renewable energy sources, ensuring reduced energy consumption and stable disinfection performance under variable operating conditions.

To achieve this aim, the following two objectives are accomplished:

- to comprehensively analyze the physicochemical processes, energy consumption characteristics, and the influence of water quality parameters (pH, turbidity, and electrical conductivity) on discharge stability and disinfection efficiency in a corona discharge water treatment system operating under renewable energy supply;
- to develop and evaluate an intelligent control algorithm capable of adapting to intermittent renewable energy generation and varying water quality conditions, and to assess its effectiveness in improving energy efficiency and system stability.

4. MATERIALS AND METHODS

This scientific study was conducted to develop and substantiate an intelligent control approach for a corona discharge water disinfection system powered by renewable energy sources. The research employed a comprehensive set of methods, including theoretical analysis, mathematical modeling, software-based simulation, and laboratory experiments. All applied methods were aimed at describing the operating mechanisms of the system and obtaining subsequent experimental and analytical results. Figure 3 below presents the structural diagram of the corona discharge water disinfection system powered by renewable energy sources.



Figure 3 : Structural diagram of a corona discharge water disinfection system powered by renewable energy sources

Figure 3 illustrates the overall structure of a water disinfection system using a corona discharge reactor powered by electrical energy obtained from renewable energy sources. The schematic shows the process of

microorganism removal from contaminated water due to the action of ozone and hydroxyl radicals generated in a high-voltage electric field, as well as the energy flow and interconnection between the system components.

The theoretical investigations were based on the physicochemical principles of corona discharge plasma. The corona discharge was generated under high-voltage conditions (5 – 30 kV), and the formation of low-temperature plasma as well as the generation of reactive oxygen species in water were considered. In the reaction medium, the ozone concentration ranged from 10 to 40 mg/L, while the formation of hydroxyl radicals was described as a function dependent on the electric field strength and discharge power. The electrical characteristics of the plasma discharge were modeled using time-varying voltage $V(t)$ and current $I(t)$ signals, and the average discharge power was calculated by integrating over the pulse period. In addition, the thermal state of the plasma–water system was described using an energy balance equation that takes into account the heat capacity, the heat transfer coefficient with the surrounding environment, and the ambient temperature. Table 2 below presents the electrical and plasma parameters of the corona discharge plasma.

Table 2: Electrical and plasma parameters of corona discharge plasma			
№	Parameter	Symbol (Unit)	Value range
1	Discharge voltage	U, kV	5 – 30
2	Electric field strength	E, V/m	$10^5 - 10^7$
3	Discharge current	I, mA	0.05 – 10
4	Pulse duration	τ , μ s	1 – 100
5	Pulse frequency	f, Hz	50 – 10^4
6	Average discharge power	P_{av} , W	10 – 1000
7	Discharge energy per pulse	W, mJ	0.1 – 50
8	Electron temperature	T_e , eV	1 – 5
9	Plasma gas temperature	T_p , K	300 – 600
10	Electron density	n_e , cm^{-3}	$10^{13} - 10^{15}$
11	Ozone concentration	CO ₃ , mg/L	10 – 40
12	Hydroxyl radical concentration	C _{OH} , mol/L	$10^{-9} - 10^{-6}$
13	Lifetime of reactive oxygen species	τ_{ROS} , s	$10^{-6} - 10^{-3}$
14	Water flow rate	Q, L/min	0.1 – 5
15	Reactor volume	V _r , L	0.5 – 10
16	Water temperature	T _w , K	293 – 313
17	Heat transfer coefficient	h, W/(m ² ·K)	5 – 100
18	Ambient temperature	T _{env} , K	293 – 308
19	Microorganism inactivation efficiency	η , %	90 – 99.99
20	Energy efficiency	ϵ , kWh/m ³	0.5 – 2.5

Table 2 summarizes the key electrical and plasma parameters governing the operation of the corona discharge, including voltage, current, electric field strength, and plasma characteristics. These parameters define the formation of reactive species and determine the efficiency and stability of the plasma-based water disinfection process.

To account for the unstable nature of power obtained from renewable energy sources, time profiles with solar radiation fluctuations of $\pm 20 - 50\%$ and wind speed variations of $\pm 25 - 45\%$ were applied. These profiles were described using stochastic models, and the influence of the

imbalance between energy generation and load demand on corona discharge operating regimes was investigated. The interrelationship between energy availability, discharge power, and key water quality parameters – pH (5.0 – 11.0), turbidity (0 – 60 NTU), and electrical conductivity (200 – 2500 $\mu\text{S}/\text{cm}$)—was incorporated into the dynamic control system.

The concept of controlling corona discharge operating regimes is based on the stochastic nature of solar and wind energy generation. Since renewable energy sources exhibit temporal variability, an adaptive control approach is required to match the discharge power with the available energy supply.

In this concept, a dynamic control system continuously monitors the availability of solar and wind energy and adjusts the corona discharge parameters accordingly. By coordinating energy input, discharge intensity, and treatment duration, the system maintains stable plasma generation while optimizing energy consumption. At the same time, key water quality parameters are taken into account to ensure effective and reliable disinfection.

Overall, the adaptive control of corona discharge regimes enables efficient operation under fluctuating renewable energy conditions, improves system stability, and supports the integration of plasma-based water treatment technologies with hybrid renewable energy systems.

To develop the intelligent control system, machine learning and reinforcement learning methods were employed. Supervised learning models were used to predict energy consumption and discharge stability, while reinforcement learning algorithms were applied to optimally select control actions under intermittent power conditions from renewable energy sources. The control actions included the discharge voltage amplitude, pulse frequency, and processing time. The control system architecture was designed as a multi-layer structure capable of acquiring sensor data in real time and generating control decisions. Overall, Table 3 below presents the parameters of the intelligent control system.

Table 3: Parameters of the intelligent control system			
Nº	Parameter	Symbol (Unit)	Value range
1	Number of input variables	N_x	6 – 15
2	Number of control actions	N_u	3
3	Voltage amplitude	U, kV	5 – 30
4	Pulse frequency	f, Hz	50 – 10^4
5	Processing time	t, s	1 – 300
6	Energy availability level	E, V/m	0.2 – 1.0
7	Discharge power	P, W	10 – 1000
8	State vector dimension	dim (S)	8 – 20
9	Action vector dimension	dim (A)	3
10	Learning rate	α	10^4 – 10^2
11	Discount factor	γ	0.90 – 0.99
12	Reward function weight	w	0.1 – 1.0
13	Number of training episodes	N_e	10^3 – 10^5
14	Sensor data sampling rate	f_s , Hz	1 – 10
15	Decision-making delay	τ_d , ms	10 – 200

Table 3 summarizes the key parameters used in the intelligent control system, including input variables, control actions, and learning-related settings. These parameters define the adaptive behavior of the control algorithms and ensure stable system performance under variable renewable energy conditions.

To implement the modeling and control algorithms of the research, the Python programming environment was used, in which the dynamic model of the corona discharge system and the temporal profiles of renewable

energy sources were implemented. Machine learning models were developed in Python using the TensorFlow and PyTorch libraries. The electric field distribution, plasma – water interaction, and thermal processes were investigated through multiphysics modeling in the COMSOL Multiphysics environment. Data exchange between the software tools was ensured, enabling the interaction between physical models and intelligent control algorithms.

The integrated modeling framework combines corona discharge system simulations with intelligent control algorithms implemented in Python and COMSOL Multiphysics environments. In this approach, Python is used for system-level modeling, renewable energy profile analysis, and the development of machine learning-based control strategies, while COMSOL Multiphysics provides detailed multiphysics simulations of the corona discharge process.

The interaction between these two environments is achieved through bidirectional data exchange. Physical parameters obtained from COMSOL simulations, such as electric field distribution, plasma-water interaction characteristics, and thermal behavior, are transferred to the Python environment for data processing and control optimization. In turn, control commands and optimized operating parameters generated by machine learning algorithms are fed back into the multiphysics model.

This coupled framework enables coordinated analysis and adaptive control of the corona discharge system under variable operating conditions. By integrating physics-based modeling with data-driven control algorithms, the proposed approach supports improved system performance, energy efficiency, and robustness when operating with renewable energy sources.

Experimental studies were conducted using a laboratory - scale corona discharge water disinfection unit. The system was equipped with a high-voltage power supply operating in the 5 – 30 kV range, a corona discharge reactor with adjustable electrode geometry, and a power stabilization module. Renewable energy sources, including photovoltaic panels and a wind energy simulator, were employed, while energy storage elements ensured continuous system operation. Water quality parameters such as pH, turbidity, and electrical conductivity were monitored using appropriate sensors, whereas electrical parameters including voltage, current, and power were measured using dedicated electrical sensors.

The experimental system represents a laboratory-scale corona discharge water disinfection setup powered by renewable energy sources. The structural configuration begins with energy generation from photovoltaic solar panels and a wind turbine, supported by an energy storage battery unit. These sources supply electrical power to the system under variable environmental conditions.

The generated energy is routed through a power stabilization module, which ensures regulated voltage and current levels before being delivered to a high-voltage power supply. The high-voltage unit, operating in the range of up to 30 kV, provides the necessary electrical conditions for initiating and sustaining corona discharge within the reactor. The corona discharge reactor constitutes the core of the system, where plasma-water interactions occur and lead to the inactivation of microorganisms and improvement of water quality.

To support precise control and experimental reliability, the system is equipped with electrical parameter sensors that continuously measure voltage, current, and power at key points in the setup. In parallel, water quality sensors monitor critical parameters such as pH, turbidity, and electrical conductivity of the treated water. All measurement data are collected and processed by a data acquisition system, enabling real-time monitoring, adjustment of operating modes, and validation of experimental results.

Overall, this structural scheme demonstrates the coordinated integration of renewable energy generation, power conditioning, high-voltage conversion, plasma-based water treatment, and comprehensive monitoring, ensuring stable operation and reproducible performance of the laboratory-scale corona discharge water disinfection system.

During the experiments, data were recorded in real time and stored for subsequent analysis and model training. The sampling frequency was selected to capture both millisecond-scale electrical transient processes and minute-scale variations in water quality parameters. The adequacy of the proposed models and control algorithms was evaluated by comparing numerical simulation results with experimental measurements, assessing stability under parametric uncertainty, performing cross-validation of machine learning models, and conducting sensitivity analysis. These

approaches were aimed at ensuring the physical validity and practical applicability of the proposed intelligent control system.

5. RESULTS AND DISCUSSION

The scientific research results are analyzed within the framework of developing and substantiating an intelligent control approach for a corona discharge - based water disinfection system operating on renewable energy sources. The study was conducted at the Institute of Electronics, Telecommunications, and Space Technologies of Satbayev University. The obtained results are structured according to the defined objectives in two directions: the first subsection provides a comprehensive analysis of physicochemical processes in the corona discharge, energy consumption characteristics, and the influence of water quality parameters (pH, turbidity, and electrical conductivity) on discharge stability and disinfection efficiency; the second subsection focuses on the development of an intelligent control algorithm adaptable to intermittent renewable energy generation and varying water quality conditions, and evaluates its effectiveness in improving energy efficiency and system stability.

5.1 Analysis of Physicochemical Processes and Energy Consumption under Renewable Energy Supply

The first objective was aimed at analyzing the physicochemical mechanisms of corona discharge plasma, energy consumption characteristics, and the influence of water quality parameters on discharge stability and disinfection efficiency under renewable energy supply conditions. Experimental and numerical modeling results demonstrated that stable corona discharge plasma formation in the voltage range of 5 – 30 kV leads to the generation of key reactive oxygen species, namely ozone (10 – 40 mg/L) and hydroxyl radicals (10^{-9} – 10^{-6} mol/L). These species play a dominant role in microorganism inactivation, providing a disinfection efficiency of 90 – 99.99% depending on the operating regime (Figure 4).

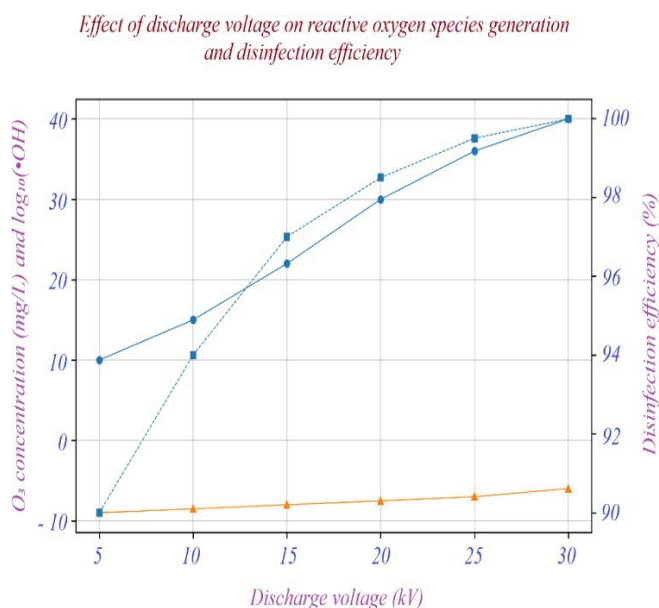


Figure 4: Influence of corona discharge operating regimes on reactive oxygen species generation and disinfection efficiency

As the corona discharge voltage increases from 5 to 30 kV, the ozone concentration rises from 10 to 40 mg/L, while the hydroxyl radical concentration increases within the range of 10^{-9} – 10^{-6} mol/L, indicating enhanced chemical activity of the plasma. The increased generation of reactive oxygen species leads to an improvement in microorganism inactivation efficiency from 90% to 99.99%, demonstrating the high effectiveness of corona discharge plasma for water disinfection.

The analysis of energy consumption revealed that the specific energy demand of the system varies within the range of 0.5 – 2.5 kWh/m³. Variations in water quality parameters, including pH (5.0 – 11.0), turbidity

(0 – 60 NTU), and electrical conductivity (200 – 2500 μ S/cm), were found to have a significant influence on discharge stability, with instability increasing up to $\pm 45\%$ under conditions of high turbidity and conductivity. This behavior confirms the strong coupling between physicochemical and electrical processes in corona discharge systems.

As water turbidity increases from 0 to 60 NTU, the instability of the corona discharge rises progressively, reaching values of up to $\pm 45\%$, which indicates a deterioration of electrical stability under highly turbid conditions. This trend demonstrates that variations in water quality significantly affect discharge behavior, confirming the strong coupling between physicochemical properties of water and electrical processes in corona discharge systems.

5.2 Evaluation of the Effectiveness of the Intelligent Control Algorithm under Variable Operating Conditions

The second objective was focused on the development of an intelligent control algorithm adaptable to variable renewable energy generation and changing water quality conditions, as well as on the evaluation of its effectiveness. Modeling and experimental results demonstrated that the proposed intelligent control system is capable of effectively regulating discharge voltage, pulse frequency, and treatment time under stochastic fluctuations of solar and wind energy in the range of ± 20 – 50%. As a result, discharge stability was maintained within ± 10 – 15%, whereas in conventional predefined control approaches this value increased to ± 25 – 35%. Figure 5 illustrates the effect of the intelligent control algorithm on discharge stability under renewable energy fluctuations.

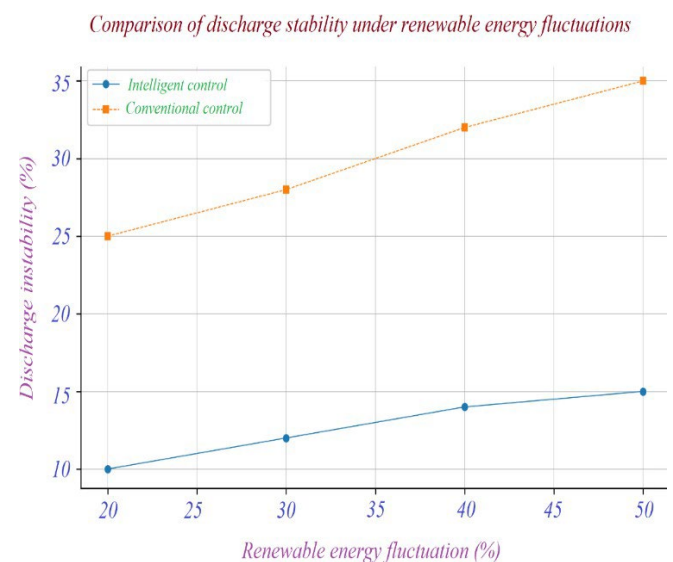


Figure 5: Effect of an intelligent control algorithm on discharge stability under renewable energy fluctuations

Under stochastic renewable energy fluctuations of ± 20 – 50%, the intelligent control system maintains corona discharge instability within ± 10 – 15%, whereas conventional predefined control methods exhibit significantly higher instability levels of ± 25 – 35%. These results demonstrate that adaptive regulation of discharge voltage, pulse frequency, and processing time substantially enhances system stability under variable energy supply conditions.

The prediction models based on machine learning demonstrated high accuracy, with the coefficient of determination ranging from $R^2 = 0.90$ to 0.97. Reinforcement learning algorithms prevented excessive power consumption under energy shortage conditions and effectively avoided discharge interruptions. As a result, the overall energy consumption of the system was reduced by 15 – 35%, while the disinfection efficiency was maintained above 95% in most operating regimes. These results clearly demonstrate the advantages of intelligent control in improving energy efficiency and system stability. Overall, Table 4 presents the results of the intelligent control system based on machine learning and reinforcement learning.

Table 4: Results of the machine learning and reinforcement learning–based intelligent control system

R ² (ML prediction)	Energy fluctuation (%)	Energy consumption reduction (%)	Discharge instability (intelligent control, %)	Discharge instability (conventional control, %)	Disinfection efficiency (%)	Voltage range (kV)
0.90	±20	15	10	25	95.0	5 – 30
0.92	±30	20	12	28	96.5	5 – 30
0.94	±40	25	13	32	97.8	5 – 30
0.96	±45	30	14	33	98.9	5 – 30
0.97	±50	35	15	35	99.5	5 – 30

The table shows that the intelligent control system achieves high prediction accuracy of the machine learning models ($R^2 = 0.90 - 0.97$) while reducing overall energy consumption by 15 – 35%. In addition, the system maintains stable discharge operation under renewable energy fluctuations and ensures disinfection efficiency above 95%.

5.3 Discussion of the Results of the Study

The results obtained in this study are explained by the strong interaction between physicochemical plasma processes, electrical discharge characteristics, the availability of renewable energy, and the adaptive control mechanisms implemented in the proposed system. The experimental and modeling results shown in Figures 4 indicate that increasing the corona discharge voltage from 5 to 30 kV leads to a proportional increase in ozone concentration (10 – 40 mg/L) and hydroxyl radical concentration ($10^{-9} - 10^{-6}$ mol/L). This directly explains the increase in microorganism inactivation efficiency from 90% to 99.99%. This behavior is consistent with the plasma energy balance and discharge power relations described by Equations (1) and (2), where higher average discharge power enhances the generation of reactive oxygen species (ROS) but also increases sensitivity to variations in water turbidity and electrical conductivity. In addition, Figure 3 and Table 4 show that real-time adaptive regulation of voltage, pulse frequency, and treatment time reduces discharge instability to $\pm 10 - 15\%$ under renewable energy fluctuations.

A key feature of the proposed method, compared with existing approaches, is the integrated consideration of renewable energy intermittency, high-voltage plasma dynamics, and variable water quality parameters within a unified intelligent control framework. Unlike conventional plasma disinfection studies operating under fixed power supply conditions, this work explicitly incorporates stochastic solar and wind energy profiles ($\pm 20 - 50\%$) and demonstrates stable system operation under these conditions (Song et al., 2022 ; Lan et al., 2024 ; Gao et al., 2023 ; Martin et al., 2024 ; Suwannarat et al., 2024). Compared with solar - powered ozonation and water treatment systems controlled by threshold or predefined logic, the proposed machine learning and reinforcement learning – based approach achieves higher energy efficiency, with energy consumption reduced by up to 35%, and significantly improved discharge stability (Hafeez et al., 2021 ; Hendrickson et al., 2020). In comparison with existing machine learning applications in water treatment systems summarized in Table 1, the novelty of this study lies in extending intelligent control concepts to corona discharge plasma systems, which have not been previously addressed (Alali et al., 2023 ; Zhang et al., 2021 ; Zhang et al., 2025).

Several limitations are inherent in the present research. First, experimental validation was conducted at a laboratory scale, and the applicability of the obtained results to full - scale or industrial systems requires further investigation. Second, the intelligent control models were trained and validated within specific ranges of input parameters (Tables 2 and 3), including discharge voltage (5 – 30 kV), turbidity (0 – 60 NTU), and electrical conductivity (200 – 2500 $\mu\text{S}/\text{cm}$). Outside these ranges, the adequacy and reproducibility of the results cannot be ensured. Third, although stochastic renewable energy profiles were considered, extreme or long-term energy shortage scenarios were not explicitly analyzed, which may affect system robustness in real-world applications.

In addition to these limitations, several disadvantages of the study can be identified. One disadvantage is the relatively high computational complexity of reinforcement learning algorithms, which may introduce delays in real-time decision-making. Another disadvantage is the dependence of control performance on accurate and reliable sensor data;

sensor noise or failures may degrade system performance. These disadvantages can be addressed in future work by implementing lightweight control architectures, hybrid model-based and data-driven control strategies, and fault-tolerant sensor processing methods.

Future development of this research may include scaling the system to pilot and industrial levels, extending the intelligent control framework to multi-reactor configurations, and incorporating predictive maintenance and fault diagnosis functions. From a mathematical and methodological perspective, challenges may arise in ensuring the convergence and stability of learning algorithms under highly non-stationary operating conditions. Experimentally, long-term operation, electrode degradation, and real environmental variability may also present difficulties. Nevertheless, overcoming these challenges would further enhance the practical applicability of intelligent, renewable energy–powered corona discharge water disinfection systems and strengthen their role as sustainable alternatives to conventional water treatment technologies.

6. CONCLUSION

Summarizing the scientific research, it can be stated that, by systematically addressing the objectives set to achieve the overall aim of the study, the following scientifically substantiated and practically significant results were obtained.

- The physicochemical processes and energy consumption characteristics of a corona discharge water disinfection system powered by renewable energy sources were clarified. The study showed that stable corona discharge operation in the voltage range of 5 – 30 kV ensures the generation of ozone at concentrations of 10 – 40 mg/L and hydroxyl radicals in the range of $10^{-9} - 10^{-6}$ mol/L. These conditions provide microorganism inactivation efficiencies of 90 – 99.99% with a specific energy consumption of 0.5 – 2.5 kWh/m³. In addition, quantitative analysis demonstrated that variations in water quality parameters, particularly turbidity and electrical conductivity, can increase discharge instability up to $\pm 45\%$. This result is explained by the fact that higher discharge power enhances the formation of reactive oxygen species while simultaneously increasing the sensitivity of the system to external physicochemical fluctuations, which distinguishes the obtained results from those reported in studies based on fixed power supply conditions.
- An intelligent control approach ensuring reliable corona discharge operation under intermittent renewable energy conditions was developed and its effectiveness was evaluated. Machine learning and reinforcement learning – based control algorithms demonstrated the ability to maintain discharge instability within $\pm 10 - 15\%$ under solar and wind energy fluctuations of $\pm 20 - 50\%$, whereas conventional predefined control methods exhibited instability levels of $\pm 25 - 35\%$. At the same time, the proposed control strategy reduced overall energy consumption by 15 – 35% while maintaining water disinfection efficiency above 95% in most operating regimes. These results are explained by the capability of the intelligent controller to adaptively coordinate discharge voltage, pulse frequency, and treatment time in real time in response to changes in energy availability and system operating conditions.
- The scientific and practical advantages of integrating intelligent control with renewable energy – powered corona discharge systems were substantiated. The obtained results confirm that combining intelligent control with corona discharge plasma significantly improves the stability and energy efficiency of water disinfection systems under non-stationary energy supply conditions. Unlike existing studies that primarily focus on electrochemical or

membrane-based water treatment processes, this work extends intelligent control concepts to high-voltage corona discharge plasma systems and demonstrates enhanced robustness to energy fluctuations and operational variability. The observed improvements are explained by the unified control framework that simultaneously accounts for renewable energy intermittency, plasma discharge dynamics, and variability in water quality parameters. These findings highlight the strong potential of the proposed approach for the development of sustainable and intelligent water disinfection technologies powered by renewable energy sources.

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