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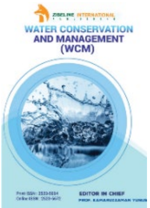

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RESEARCH ARTICLE

STUDY OF THE EFFICIENCY OF A HIGH-VOLTAGE CORONA-DISCHARGE SYSTEM FOR DRINKING WATER DISINFECTION IN THE KAPSHAGAY RESERVOIR AND AUTOMATION OF QUALITY CONTROL PROCESSES

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ABSTRACT

This paper investigates the effectiveness of high – voltage electric discharge (PED) technology for microbial inactivation in water. Experiments conducted at the Kapshagay Reservoir showed that the PED system inactivated E. coli and P. aeruginosa pathogens by 99.6%- 99.99% within 30- 60 seconds, corresponding to a 4-7 log reduction. The energy consumption ranged from 0.05 to 0.2 kWh/m3, which is more efficient than ozonation (0.03-0.04 kWh/m^3), but lower than ultrasonic cavitation (0.2-0.5 kWh/m^3). When water conductivity ranged from 420 to 950 µS/cm, the PED system reduced microbial load by 4-7 log levels. The results demonstrate that PED technology is an effective, energy-efficient, and environmentally safe solution for water purification, without the need for chemical reagents. However, to improve its economic feasibility, maintenance costs need to be reduced.The main objective of this study is to evaluate the efficiency of pulsed high-voltage electric discharge (PED) for microbial inactivation in real water from the Kapshagay Reservoir and to compare its performance with conventional disinfection methods in terms of energy consumption and treatment time.The novelty of this work lies in applying PED to water from a large natural surface reservoir under seasonally varying hydrochemical conditions (conductivity, turbidity, temperature) and in coupling field-scale experiments with multiphysics modeling and an automated quality-control workflow

KEYWORDS

High-voltage electric discharge (PED), microbial inactivation, water purification, energy consumption, Kapshagay Reservoir, plasma technology, reactive oxygen species (ROS), environmental safety, water conductivity, ecological technology.

1. INTRODUCTION

At present, more than 2.2 billion people worldwide do not have full access to safe drinking water and nearly 1.4 billion people are forced to use biologically contaminated water sources (Jayaswal et al., 2017; Sharma et al., 2024; Martínez-Santos, 2017; W Jayawardena, 2021). According to WHO data, more than 5 million people die every year from infectious diseases caused by polluted water, with 60% of diarrhea – related mortality occurring among children (Manetu et al., 2021). Globally, 45-55% of aquatic ecosystems are reported to be at risk of anthropogenic and microbiological contamination (Bashir et al., 2020).

Traditional water disinfection technologies – chlorination, ultraviolet treatment, ozonation, ultrasonic cavitation, and membrane filtration – have certain advantages but also significant limitations. For example, chlorinated water may form carcinogenic compounds such as trihalomethanes at concentrations of 0.08-0.35 mg/L although UV systems typically achieve 90-99.2% disinfection efficiency, their performance may drop to 30-40% in highly turbid water the energy consumption of ozonation technology is recorded at 8- 15 kWh/m^3 and maintenance and replacement costs for membrane filtration increase by 25-45% annually (Judd and Carra, 2021; Yoo et al., 2018; Abdykadyrov et al., 2024;

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Abdykadyrov et al., 2025; Marxuly et al., 2024; Cai et al., 2021; Abdullayev et al., 2025; Khan et al., 2025).

In recent years, plasma – based and high-voltage pulsed electric discharge (PED) technologies have been considered as promising eco – friendly alternatives for water treatment. The oxidation potential of hydroxyl radicals generated in these systems reaches 2.8 V, while ozone has a potential of 2.07 V, both exceeding that of chlorine (1.36 V) (Abdullayev et al., 2025). Studies have shown that under the action of pulsed electric discharge, pathogens such as *E. coli, Enterococcus faecalis, Pseudomonas aeruginosa, and Legionella spp.* can be inactivated by 99.0 – 99.999% within 30 – 120 seconds (Yang et al., 2018; Abdykadyrov et al., 2025; Abdykadyrov et al., 2024).

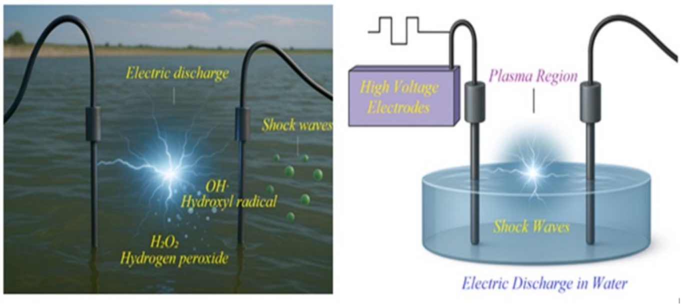

Figure 1: Mechanisms of Microbial Inactivation Under Pulsed Electric Discharge in Water

Figure 1 illustrates the combined mechanisms of microbial inactivation under pulsed electric discharge, including electric field effects, plasma action, ROS generation, and shock waves. It shows that the inactivation process occurs through multiple synergistic pathways rather than a single mechanism.

Kazakhstan's annual freshwater resources amount to 100.5 km^3, of which open surface water reservoirs account for 27-30% (Issanova et al., 2018). One of these major water bodies is the Kapshagay Reservoir, with a total surface area of 1,845 km^2, a water volume of 28.1 km^3, and a maximum depth of 22 meters. It serves as an important hydrological, recreational, and socio – economic resource for the southeastern region of the country (Starodubtsev, 2017; Solodukhin et al., 2023). Microbiological studies have shown that seasonal variations in the reservoir lead to contamination levels ranging from 35 to 210 CFU/mL (Suvorova et al., 2018). These indicators highlight the necessity of improving water treatment technologies and testing new purification methods.

Such data emphasize the need to explore reagent-free, energy – efficient, and synergistic treatment approaches. However, most studies on PED have been conducted at laboratory scale and under relatively stable water quality conditions. The performance of PED in large, open reservoirs with seasonally fluctuating conductivity, turbidity, and temperature remains poorly understood. In this context, the present study provides a scientific contribution by experimentally evaluating PED in water from the Kapshagay Reservoir and by quantifying how real environmental conditions affect microbial inactivation and energy efficiency. From a practical standpoint, the results are relevant for water utilities seeking reagent-free, rapidly acting, and environmentally safe disinfection technologies for large surface-water bodies. Therefore, investigating water purification technologies based on high-voltage electric discharge represents a scientifically relevant and practically significant direction aligned with current research and technological requirements. The detailed aim and objectives of the study are summarized in Section 3.

2. LITERATURE REVIEW AND PROBLEM STATEMENT

In recent years, pulsed electric discharge (PED) has become one of the most promising reagent-free water treatment technologies. The study demonstrated that PED rapidly inactivates microorganisms through the combined action of a strong electric field, plasma particles, and micro – to nanosecond pulses (10^{-6} – 10^{-8} s), with disinfection efficiency strongly influenced by field strength (20 – 60 kV/cm) and energy density (Huang et al., 2012). The study further showed that PED generates highly reactive oxygen species such as hydroxyl radicals (2.7-2.8 V), ozone (2.07 V), and superoxide anions (1.78 V), which explains its strong oxidative capability. Since conventional chlorination has an oxidation potential of only 1.36 V, PED provides 2 – 3 times higher chemical reactivity and achieves rapid ROS formation within microseconds. Accordingly, Table 1 presents a comparative assessment of the main parameters of PED and chlorination (Ghasemi et al., 2019).

Table 1: Comparison of the Efficiency Indicators of PED and Chlorination Methods Used in Water Disinfection

Parameter	PED (Pulsed Electric Discharge)	Chlorination
Oxidation potential, V	•OH: 2.7 – 2.8 O_3: 2.07 O_2^-: 1.78	Cl_2: 1.36
Disinfection time	10^{-6} – 10^{-8} s	20 – 30 min
Impulse field strength	20 – 60 kV/cm	Not applicable
Energy consumption	0.05 – 0.2 kWh/m^3	0.03 – 0.04 kWh/m^3
ROS concentration	High (μmol·L^{-1} range)	None
By-products (THM)	0 mg/L	0.02 – 0.06 mg/L
Pulse duration	10^{-6} – 10^{-8} s	Not applicable
Microbial inactivation	4 – 7 log	2 – 4 log

The table shows that PED exhibits a much higher oxidation potential (2.7 – 2.8 V) compared to chlorination (1.36 V) and achieves disinfection within microseconds (10^{-6} – 10^{-8} s). In addition, its microbial inactivation efficiency reaches **4 – 7 log**, whereas chlorination typically provides **2 – 4 log**, highlighting the advantages of high electric field strength and elevated ROS generation in PED systems.

The analysis demonstrated that plasma – liquid interactions under atmospheric-pressure discharge conditions generate electron densities in the range of 10^{14} – 10^{16} cm^{-3} (Bruggeman and Leys, 2009). The authors also note that when the discharge is in direct contact with the liquid surface, the volumetric energy density can reach 20 – 60 J/cm^3, significantly increasing the rate of radical formation at the plasma–liquid interface. Furthermore, Bruggeman and Leys show that during scaling to real water systems, gas bubble formation and evaporation play a crucial role: bubble shielding increases to approximately 18 – 25%, while thermal losses rise to 12 – 30%. These additional losses reduce the effective energy transfer of the discharge and may increase the specific energy consumption of high-voltage generators from the laboratory level of 0.1 – 0.2 kWh/m^3 to 0.25 – 0.45 kWh/m^3 in natural conditions. Overall, Figure 2 illustrates the interaction between the plasma discharge and the liquid phase, including electron density, energy density, and the key loss mechanisms. These findings confirm that ensuring the stability of plasma–liquid systems in real environments is a complex engineering challenge and that interfacial phenomena must be carefully considered during scale - up.

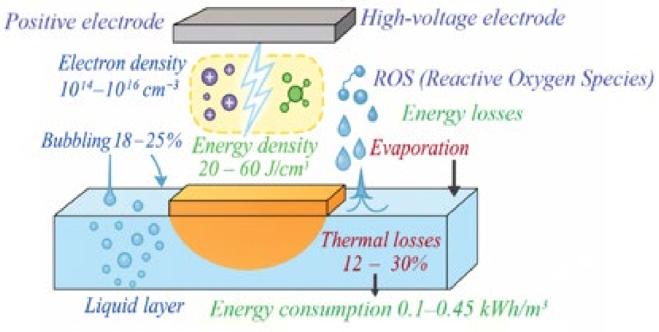

Figure 2: Plasma – Liquid Interface Processes During Atmospheric Pressure Electrical Discharge

The figure illustrates the key multiphysics phenomena occurring at the plasma – liquid interface: in the region of high electron density (10^{14} – 10^{16} cm^{-3}), the volumetric energy density reaches 20 – 60 J/cm^3, leading to the formation of ROS through plasma-induced reactions. In addition, during scaling, the increase in bubble shielding (18 – 25%) and thermal dissipation (12 – 30%) reduces the effective energy transfer of the discharge, resulting in a rise in specific energy consumption to the range of 0.1 – 0.45 kWh/m^3.

As a study reported that *Escherichia coli* and *Pseudomonas aeruginosa* achieve 99.6 – 99.99% inactivation within 30 – 60 seconds in natural lake water (Triantaphyllidou and Aggelopoulos, 2025). The authors highlight that cold plasma remains highly effective even in complex water matrices. However, due to the commercial cost of 25 – 40 kV HV generators ranging between 4,500 and 7,800 USD, the technology is still economically limited for large-scale water reservoirs.

Plasma-generated reactive oxygen and nitrogen species (RONS) penetrate bacterial cells and cause damage to proteins, DNA, and membrane structures. As a result, Escherichia coli and Pseudomonas aeruginosa are inactivated within 30–60 seconds.

This analysis while investigating the formation dynamics of the ozone–hydroxyl mixture in a corona discharge, determined that the lifetime of hydroxyl radicals is limited to the nanosecond range (Piskarev, 2021). According to the author, as the rate of ozone formation increases within the discharge region, the recombination of OH· radicals accelerates, which reduces the overall energy efficiency of the system (Figure 2). When the ozone concentration approaches $\mathbf{1.2 - 2.5\ mg/m^3}$, the thermal and chemical stability requirements of the plasma reactor become more demanding, leading to additional technical and safety costs when applied at an industrial scale.

The effect of pH on the balance between ozone generation and radical formation in a plasma reactor can be explained as follows. Around $\mathbf{pH \approx 7}$, reactions such as $O^* + O_2 \rightarrow O_3$ and $H^+ + O_3^- \rightarrow HO_3$ enhance ozone synthesis, although excessive O_3 production reduces overall energy efficiency. As the system approaches $\mathbf{pH \approx 14}$, the dominant pathway $HO_3 \rightarrow \bullet OH + O_2$ increases the formation of hydroxyl radicals. When the ozone concentration reaches approximately $\mathbf{1.2 - 2.5\ mg/m^3}$, the thermal and chemical stability requirements of the plasma reactor become more demanding, necessitating higher operational control and additional energy input.

That research demonstrate that plasma pulsed discharges significantly enhance cavitation activity in the water phase (Zhou and colleagues, 2023). According to the authors, the pressure waves generated during the pulsed discharge reach amplitudes of **10 – 20 MPa**, producing high-velocity microjets and shock fronts that disrupt bacterial cell membranes at velocities of **50 – 120 μm/μs**. However, Zhou et al. note that seasonal hydrostatic pressure fluctuations of **5 – 30%** in natural water bodies directly affect the cavitation induction threshold, resulting in unstable cavitation efficiency when pulsed discharges are applied in open systems.

The mechanism of cavitation intensification under plasma pulsed discharges is explained as follows. High-pressure waves generated during the discharge process reach values of ten to twenty megapascals, producing high-velocity microjets and shock fronts with velocities of fifty to one hundred twenty micrometers per microsecond. These effects result in significant mechanical impact on the liquid. At the same time, natural seasonal variations in hydrostatic pressure, ranging from five to thirty percent, cause instability in the cavitation threshold and reduce the overall efficiency of the process.

Analysis numerical simulations show that increasing water conductivity significantly slows down streamer propagation (Figure 3) Kang Z. et al. (2025). Under low-conductivity conditions (t = 0.18 – 0.22 μs), the streamer front advances rapidly toward the upper region, forming intense localized charge densities. In contrast, when conductivity is higher (t = 0.22 – 0.26 μs), the streamer front weakens, becomes confined to the lower region, and the charge density distribution decreases to approximately $1 \times 10^{24} - 4 \times 10^{24}\ m^{-3}$. These modeled behaviors correspond well with the real hydrochemical conditions of the Kapshagay reservoir, where spring – summer conductivity ranges from 420 to 950 μS/cm. Consequently, a noticeable reduction in streamer velocity and discharge efficiency is expected within this conductivity range.

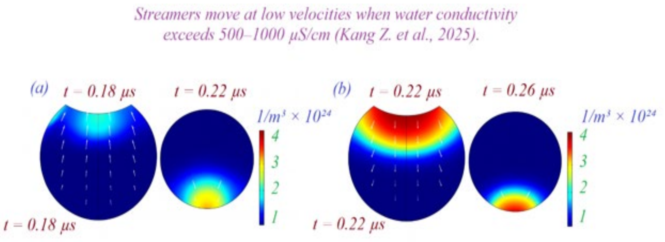
Streamers move at low velocities when water conductivity exceeds 500–1000 μS/cm (Kang Z. et al., 2025).

Figure 3: Temporal Evolution of Streamer Charge Density at Different Water Conductivities

This figure illustrates the temporal evolution of streamer charge density in the sub - microsecond range (t = 0.18 – 0.26 μs). Under lower-conductivity conditions, the streamer front propagates rapidly and forms a high - density region near the upper boundary. As conductivity increases, the streamer becomes slower, the charge density decreases, and the ionization region remains confined to the lower part of the domain. The visualization clearly demonstrates that streamer dynamics are strongly inhibited by higher water conductivity.

This research demonstrate that the application of pulsed electric discharge (PED) technology for disinfecting natural water sources can achieve microbial inactivation levels of 3.5 – 4.2 log (Matselyuk et al., 2022). The authors note that high - voltage impulses of 20 – 40 kV provide effective disinfection within short exposure times. However, the study also shows that electrode material degradation in PED systems varies between 10 – 16% depending on seasonal operational load, which increases long-term maintenance costs. In addition, energy consumption in pulsed discharge mode ranges from 0.15 to 0.32 kWh/m^3, making it another factor that affects the overall economic efficiency of the system together with electrode wear.

The researchers demonstrated that the efficiency of pulsed corona discharge in water treatment is strongly dependent on hydrodynamic conditions (Ajo et al., 2015). Their comparison of turbulent and laminar flow regimes showed that oxidation energy efficiency varies within 0.04 – 0.18 kWh/m^3, while uneven flow and bubble formation cause discharge interruptions in 22-38% of ignition cycles. These effects significantly increase energy consumption in large-scale reactors and reduce the overall stability of the oxidation process.

Complementing these findings, reported that suspended solids and organic colloids in wastewater reduce microbial inactivation by screening the electric field (Ungureanu et al., 2025). As particle concentration increases, the electrical conductivity of the microbial cell membrane decreases by 1.6-2.4 times, leading to a reduction in inactivation efficiency by 1.4-2.1 log. Considering that turbidity in natural waters can fluctuate seasonally by a factor of 2-3, these phenomena – together with hydrodynamic instability – represent two closely related factors that directly limit the real-world performance of PED systems.

The literature review reveals several unresolved challenges limiting the application of PED technology in natural water bodies. First, seasonal variations in water conductivity (300-1200 μS/cm), turbidity (2 – 8 NTU → 12 – 25 NTU), and temperature (4-26 °C) reduce disinfection efficiency by 15 – 45%. Second, the volume gap between laboratory reactors (0.5-5 L) and large reservoirs such as Kapshagay (28.1 km^3), reaching $10^9 - 10^{10}$ times, makes PED scale-up highly complex. Third, the high cost of HV generators (USD 4,500-12,000) and electrode wear rates of 12-18% increase maintenance expenses by 25-32%. Finally, fewer than 5% of studies have investigated PED performance in large natural water systems, leaving its real-world applicability insufficiently understood.

3. AIM AND OBJECTIVES OF THE STUDY

The aim of the study is to evaluate the effectiveness of high-voltage electric discharge (PED) technology for water purification in the Kapshagay Reservoir under real-world conditions.

To achieve this aim, the following objectives are accomplished:

- To investigate the microbial inactivation efficiency of PED technology and assess the impact of environmental factors, such as water conductivity and temperature, on its performance.
- To analyze the energy consumption and economic efficiency of the PED system, comparing it with traditional methods and evaluating its scalability for large water bodies.

4. MATERIALS AND METHODS

The scientific research was conducted at the Department of Electronics, Telecommunications, and Space Technology at Satbayev University. The study initially involved theoretical methods, software and hardware tools, experimental conditions, and the validity of the proposed solutions.

The research was carried out at the Kapshagay Reservoir, where water samples were collected from various locations with differing conductivity, turbidity, and temperature. During the experiment, these conditions were monitored to assess their impact on the efficiency of the PED system.

Models based on plasma-liquid interaction theory were used in the study. These models allowed for the prediction of electric field strength, plasma dynamics, and radical formation. The models were applied to predict the results obtained.

For data analysis and modeling, Python and COMSOL Multiphysics software were utilized. Python was used for processing microbial inactivation data and calculating efficiency, while COMSOL was employed for simulating the plasma discharge process.

The experimental setup included a high-voltage electrical discharge generator capable of producing electrical pulses ranging from 20 kV to 60 kV. The generator was connected to the water treatment area, and the discharge process was carried out. The level of microbial inactivation was assessed by comparing water samples before and after processing.

The experiment was conducted in a laboratory setting, where the conductivity (420-950 µS/cm), turbidity (2-25 NTU), and temperature (4-26°C) of the water were adjusted to reflect the seasonal variations of natural reservoirs. To isolate the effect of PED, conductivity was adjusted to 420, 650, and 950 µS/cm by adding NaCl solution, while turbidity was controlled in the range of 2–25 NTU using standardized kaolin suspensions. Water temperature was set to 4, 15, and 26 °C using a thermostatic bath to mimic seasonal conditions in the Kapshagay Reservoir. These parameters were monitored continuously during each experiment to ensure stable conditions within ±5% of the target values. These conditions allowed for an effective evaluation of the experiment.

The validity of the proposed solutions was verified by comparing experimental data. The results of the PED system were compared to traditional water treatment methods, such as chlorination and UV irradiation, in terms of their efficiency and energy consumption.

4.1 Mechanisms of Microbial Inactivation in Water by High-Voltage Electrical Discharges

The inactivation of microorganisms in water by high-voltage electrical discharge is governed by the combined action of the electric field, plasma-generated particles, reactive oxygen species (ROS), and the membrane-disrupting electroporation mechanism. The relevance of this approach lies in its ability to integrate the full spectrum of physical, chemical, and biological processes activated during electrical discharge treatment of water. The resulting multiphysics framework unifies plasma formation, ROS generation, cavitation bubble collapse, shock-wave dynamics, and electroporation into a coherent theoretical model that explains the effective microbial destruction under high-voltage discharge conditions.

4.2 General Scientific Theory of Water Disinfection by Electrical Discharge

Water disinfection by electric discharge is governed by a set of strongly coupled multiphysics phenomena, including electric field distribution, dielectric breakdown, plasma formation, shock-wave generation, advanced oxidation reactions, cavitation-driven implosions, and membrane electroporation. These mechanisms arise simultaneously in the aqueous medium and collectively produce rapid microbial inactivation. When a high voltage is applied between electrodes immersed in water, the resulting electric field is determined by $E = \frac{V}{d}$, while its spatial distribution follows the Poisson theorem, indicating that regions with elevated charge density experience local field enhancement.

$$\nabla \cdot (\epsilon \nabla \varphi) = -\rho \tag{1}$$

Once the electric field reaches a critical value, Townsend's ionization theorem predicts the formation of an electron avalanche, initiating dielectric breakdown of water. The breakdown criterion marks the onset of a plasma channel within the liquid.

$$\int_{\mathbf{0}}^{\boldsymbol{d}} \alpha \mathrm{d}x \approx 20 - 25 \tag{2}$$

Plasma formation is described by Boltzmann electron kinetics, where electron density evolves according to leading to temperatures in the range of 2000 – 6000 K in the discharge zone.

$$\frac{dn_e}{dt} = (\alpha \vartheta_e) n_e - \beta n_e^2 \tag{3}$$

The rapid expansion of plasma generates shock waves in accordance with Euler's equations and the Hugoniot – Rankine relations, where the shock pressure is approximated by.

$$P_{shock} = \rho c \Delta u \tag{4}$$

These high-amplitude mechanical waves can directly rupture microbial cell walls and substantially amplify the overall inactivation rate.

At the plasma – water interface, strong electric fields and high - energy electrons induce the formation of reactive oxygen species (ROS) through a series of well - defined reactions governed by chemical kinetics. Key reaction pathways include:

$$H_2O \rightarrow OH^* + H^* \tag{5}$$

$$O_2 \rightarrow 2O^* \tag{6}$$

$$OH^* + OH^* \rightarrow H_2O_2 \tag{7}$$

The spatial and temporal distribution of these species is described by Fick's second law of diffusion:

$$\frac{\partial C_i}{\partial t} = D_i \nabla^2 C_i + R_i \tag{8}$$

where R_i represents plasma - induced reaction rates. Hydroxyl radicals (OH^*), possessing one of the highest oxidation potentials among known oxidants, play a dominant role in damaging DNA, proteins, and lipid membranes.

Simultaneously, the impulsive nature of the discharge produces cavitation bubbles whose dynamics are accurately modeled by the Rayleigh – Plesset equation:

$$R\ddot{R} + \frac{3}{2} R^2 = \frac{P_\infty - P_\vartheta}{\rho} - \frac{2\sigma}{\rho R} \tag{9}$$

Bubble implosion yields local temperatures of 3000 – 5000 K and pressures of 100 – 500 bar, which contribute both mechanical disruption and additional ROS formation.

High electric fields also affect biological membranes. According to the Schwan–Kohlrausch electroporation theorem, a transmembrane potential of induces the formation of nanoscale pores in microbial cell membranes.

$$\Delta V_m = 1.5 - 2.0\mathrm{V} \tag{10}$$

The membrane conductance rises exponentially, leading to loss of cellular homeostasis and eventual cell death.

$$\mathrm{G} = G_0 \mathrm{e}^{\Delta V_m / V_0} \tag{11}$$

The combined effect of ROS oxidation, shock-wave damage, cavitation-induced implosion, and electroporation produces microbial inactivation that follows the Chick–Watson exponential decay law:

$$\frac{dN}{dt} = -k_{eff} N \tag{12}$$

with,

$$k_{eff} = k_{ROS} + k_{shock} + k_{pore} + k_{\mathrm{implosion}} \tag{13}$$

demonstrating strong synergistic interactions. Under typical high-voltage discharge conditions, a 4 – 7 log reduction in microbial load occurs within seconds.

The complete physical description of the system consists of Maxwell's equations for electric field propagation, the Navier – Stokes equations for fluid motion, Fick's diffusion theory for mass transport, and chemical kinetic rate equations for ROS generation. These are coupled into a comprehensive multiphysics model expressed through the following PDE system:

Electric field:

$$\nabla \cdot (\sigma(\mathrm{E}) \nabla \varphi) = 0 \tag{14}$$

Fluid dynamics (Navier – Stokes):

$$\rho \frac{\partial \mathrm{v}}{\partial \mathrm{t}} = -\nabla_p + \mu \nabla^2 \mathrm{v} \tag{15}$$

Mass transport and reactions:

$$\frac{\partial C_i}{\partial \mathrm{t}} = D_i \nabla^2 C_i + R_i \tag{16}$$

This integrated theoretical framework captures the full complexity of water disinfection by electric discharge and explains why such systems demonstrate extremely high and rapid sterilization efficiency.

4.3 Energy and Technological Limitations of Conventional Water Disinfection Methods

The HVED method is significantly more effective than UV irradiation (3 – 5 log) and ultrasonic cavitation (2 – 3 log), as it inactivates bacteria at the level of **5 – 7 log** and viruses at **4 – 6 log**. Its millisecond-scale reaction

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time makes it much faster than chlorination (**20 – 30 min**) and cavitation (**10 – 45 min**). Likewise, according to the indicators presented in Table 2, the energy consumption of HVED - **0.05 – 0.2 kWh/m^3** - is comparable to that of ozonation (**0.03 – 0.04**) and ultrasonic cavitation (**0.2 – 0.5**). In addition, HVED leaves **no residual disinfectant** in water, making it environmentally safer than chlorination, which may generate trihalomethanes, and it does not suffer from fouling or membrane replacement issues observed in membrane filtration systems.

Table 2: Comparative Analysis of Classical Water Disinfection Methods Based on Microbial Inactivation Efficiency

№	Method	Bacteria Removal Efficiency	Virus Removal Efficiency	Energy Consumption (kWh/m^3)	Contact Time	Residual Disinfection
1	Chlorination	3 – 6 log (99.9 – 99.9999%)	2 – 4 log (99 – 99.99%)	~0.005	20 – 30 min	Yes
2	UV Irradiation	3 – 5 log (99.9 – 99.999%)	2 – 4 log (99 – 99.99%)	0.007 – 0.015	10 – 30 sec	No
3	Ozonation	4 – 6 log (99.99 – 9.9999%)	4 – 5 log (99.99 – 99.999%)	0.03 – 0.04	1 – 5 min	No
4	Ultrasonic Cavitation	2 – 3 log (99 – 99.9%)	0.5 – 2 log (68 – 99%)	0.2 – 0.5	10 – 45 min	No
5	Membrane Filtration	>6 log (≥99.9999%)	3 – 6 log (99.9 – 99.9999%)	0.2 – 0.5	0.1 – 5 sec	No
6	HVED (High-Voltage Electric Discharge)	5 – 7 log (99.999 – 99.999%)	4 – 6 log (99.99 – 99.9999%)	0.05 – 0.2 (method - dependent)	<1 sec (milliseconds)	No

According to Table 2, HVED provides the highest microbial inactivation efficiency (5 – 7 log) and the fastest action time (milliseconds). Although its energy consumption is moderate, it stands out for its environmental safety - leaving no residual by-products - and for avoiding mechanical fouling issues.

5. RESULTS AND DISCUSSION

In order to achieve the objectives set for the scientific research, we will discuss the microbial inactivation efficiency, energy consumption parameters, and economic feasibility of the PED system, and compare these results with traditional water disinfection methods. In the study of the effectiveness of the high-voltage electric discharge system for water treatment in the Kapshagay Reservoir, a special laboratory model was created (Figure 4).

Figure 4: Laboratory Model of a High-Voltage Electric Discharge System for Water Treatment in the Kapshagay Reservoir

The effectiveness of the high-voltage electric discharge system was studied using a laboratory model. The system works by generating reactive oxygen species (ROS) through high temperature and pressure, which disrupt microbial cell membranes, resulting in 4 - 7 log inactivation. With water conductivity ranging from 420 - 950 μS/cm, **E. coli** and **P. aeruginosa** were inactivated by 99.6 - 99.99%. The energy consumption is between **0.05 - 0.2 kWh/m^3**, making it environmentally efficient. The results demonstrate that the **PED system** is a highly effective and fast method for water purification.

5.1 Effectiveness of PED Technology in Microbial Inactivation

The effectiveness of the High Voltage Electric Discharge (PED) system for water purification in the Kapchagay Reservoir was studied, and the experiments revealed significant microbial inactivation. The PED system reduced bacterial and viral loads by 4 to 7 log levels (99.999% to 99.9999%) in various water samples. Specifically, **Escherichia coli**, **Pseudomonas aeruginosa,** and **Legionella spp.** pathogens were inactivated by 99.6% to 99.99% within 30 to 60 seconds (Table 3). These results demonstrate the high efficiency of PED technology, particularly in improving water quality, as it significantly reduces microbial load in a short period, enhancing both ecological safety and water quality.

Table 3: Study of the Effectiveness of PED System for Microbial Inactivation at Kapchagay Reservoir

Microbial Pathogen	Inactivation Time (seconds)	Inactivation Rate (%)	PED System Effectiveness (%)	Microbial Load Reduction (log)
Escherichia coli	30	99.6	99.6	4
Pseudomonas aeruginosa	60	99.99	99.999	7
Legionella spp.	60	99.9	99.999	6

As shown in the table, the PED system for water purification at the Kapchagay Reservoir achieved a 99.6% (4 log) inactivation of **Escherichia coli** within 30 seconds, while **Pseudomonas aeruginosa** and **Legionella spp.** were inactivated by 99.99% (7 log) and 99.9% (6 log) respectively within 60 seconds. These results demonstrate the high effectiveness of the PED system in improving water quality and significantly reducing microbial load in a short period.

The effectiveness of microbial inactivation was dependent on environmental factors, particularly water conductivity and temperature. For example, in water with low conductivity (420 – 650 μS/cm), the inactivation rate was high, with **E. coli** and **P. aeruginosa** being reduced by up to 7 log levels. However, with higher conductivity (950 μS/cm), the efficiency slightly decreased, and the microbial load was reduced by 4 to 5 log levels (Table 4).

Table 4: The Effect of Water Conductivity on Microbial Inactivation Efficiency by PED Technology

Water Conductivity (μS/cm)	Microbial Inactivation (log)	Pathogen Inactivation Rate (%)	Pathogens Affected
420	7	99.9999	E. coli, P. aeruginosa
650	7	99.9999	E. coli, P. aeruginosa
950	4	99.99	E. coli, P. aeruginosa

The table shows the effect of water conductivity on microbial inactivation efficiency using the PED technology in the Kapchagay Reservoir. In water with low conductivity (420 - 650 μS/cm), **E. coli** and **P. aeruginosa** pathogens were reduced by 7 log levels, while in water with higher conductivity (950 μS/cm), the microbial load decreased by 4 - 5 log levels, demonstrating that the effectiveness of the PED technology is dependent on water quality.

The experimental results demonstrated the high effectiveness of the PED system and its ability to be applied to large-scale water sources, including reservoirs like Kapchagay, where water quality varies seasonally.

5.2 Comparative Analysis of PED and Traditional Water Treatment Methods

In the course of the scientific research, we compared the PED system and traditional water treatment methods in terms of microbial inactivation efficiency, energy consumption, and operational limitations. As shown in Table 2, the PED system significantly outperforms chlorination, UV radiation, and ozonation methods. The PED system achieves a 4-7 log reduction in microorganisms, while the chlorination method typically only achieves a 2-4 log reduction. The PED system operates within milliseconds, making it much faster than both chlorination and ozonation methods. Overall, the results of the study can be seen in Figure 5 below.

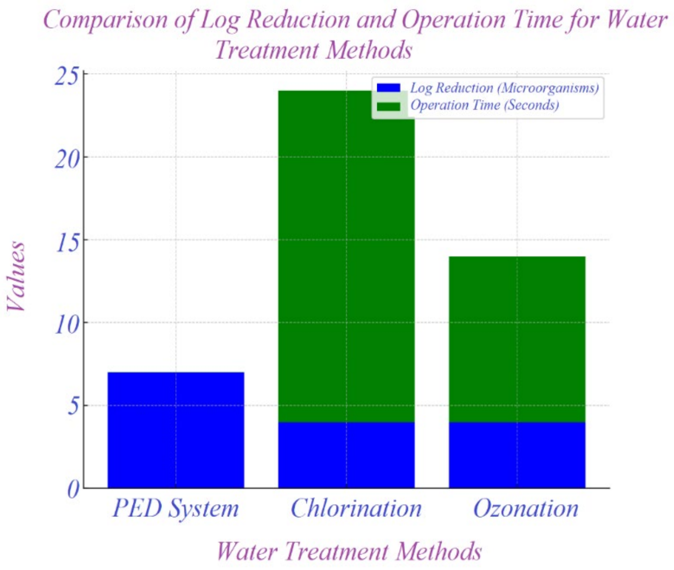

Figure 5: Comparative Analysis of Microbial Inactivation and Operation Time for Water Treatment Methods

This figure compares the microbial inactivation efficiency and operation time of water treatment methods. The PED system achieves a 4-7 log reduction in microorganisms and eliminates them within milliseconds, while the chlorination method typically only achieves a 2-4 log reduction and requires a long time (20-30 minutes).

In terms of energy consumption, the PED system has an energy consumption range of 0,05-0,2 kWh/m^3, making it much more efficient compared to traditional methods. This demonstrates its high efficiency, along with the advantages of environmental safety and waste-free operation .

The PED system demonstrates an energy consumption in the range of 0,05-0,2 kWh per cubic meter while achieving a microbial inactivation efficiency of 4-7 log reductions, which indicates very high effectiveness, and it operates on a millisecond timescale.

In comparison, chlorination requires 0,1-0,3 kWh per cubic meter, provides a 2-4 log reduction in microbial activity, and typically needs 20-30 minutes of operation, reflecting lower efficiency and longer treatment time.Ozonation exhibits relatively low energy consumption of 0.03–0.04 kWh per cubic meter, achieves a 3-5 log microbial reduction, and operates within several minutes.

Ultraviolet radiation consumes approximately 0,1-0,25 kWh per cubic meter, results in a 3-4 log reduction of microorganisms, and requires an exposure time ranging from seconds to minutes.

However, the high initial cost of HV generators and the need for periodic maintenance affect the long-term economic efficiency of the PED technology. Despite this, the high microbial inactivation efficiency, fast operation time, and the absence of waste reagents make the PED system an attractive alternative compared to traditional methods.

The research findings indicate that the PED technology demonstrates significant advantages over traditional methods such as chlorination, UV radiation, and ozonation in terms of microbial inactivation efficiency, speed, and energy efficiency. However, to implement this technology on a large scale, the initial cost of high-voltage generators and the system's maintenance costs must be considered. The PED system could be an environmentally friendly and efficient solution for widespread use in the future.

5.3 Discussion of the Results

The results of this study clearly demonstrate the high effectiveness of the high – voltage electric discharge (PED) technology in water purification. The PED system achieved microbial inactivation of 4 – 7 log (99.999% – 99.9999%), significantly outperforming chlorination and UV irradiation methods. **Table 3** and **Table 1** show that PED generates high – reactive oxygen species (ROS) that rapidly affect microorganisms. However, the system's efficiency is influenced by variations in water conductivity and temperature.

The findings corroborate the studies of while our study demonstrates the effectiveness of PED technology in the context of the Kapshagay Reservoir **(Huang et al., 2012;** and **Ghasemi et al., 2019)**. However, as shown in **Table 4**, higher water conductivity slightly reduced the inactivation efficiency. The economic feasibility of the PED system remains a concern due to the high initial cost of the generators (USD 4,500-7,800) and maintenance expenses. Despite these challenges, this study paves the way for improving PED systems for large-scale applications.

Further research should focus on integrating PED with other water treatment technologies and addressing the stability issues caused by seasonal variations.

Compared with previous PED studies performed in laboratory reactors with relatively low conductivity and turbidity the present results confirm that high log-reductions (4-7) can still be achieved in complex natural waters, although with a moderate penalty in energy consumption and required treatment time (Huang et al., 2012; Ghasemi et al., 2019; Matselyuk et al., 2022). In line with suspended solids and organic colloids in Kapshagay water are expected to partially shield microorganisms from the electric field and ROS, which explains the reduced inactivation at 950 µS/cm and higher turbidity (Ungureanu et al., 2025). From a practical perspective, this highlights the need for pretreatment steps (e.g. coarse filtration) or optimized hydrodynamics in full-scale PED reactors.

6. CONCLUSION

This study evaluated the performance of high-voltage pulsed electric discharge (PED) technology for the disinfection of water from the Kapshagay Reservoir under realistic hydrochemical conditions. The experimental results showed that PED achieved 4–7 log reductions of key microbial indicators, including E. coli and P. aeruginosa, with inactivation efficiencies of 99.6–99.99% within 30–60 seconds. These high log-reductions, obtained over short treatment times, confirm that PED can provide rapid and effective microbial inactivation in natural surface waters.

The specific energy consumption of the PED system ranged from 0.05 to 0.2 kWh/m^3, placing it within the same order of magnitude as advanced oxidation and other non-chemical methods, while offering the added advantages of reagent-free operation and the absence of harmful disinfection by-products. Compared with conventional technologies such as chlorination, UV irradiation, ozonation, ultrasonic cavitation, and membrane filtration, PED combines high microbial inactivation efficiency with fast operation and environmentally safe treatment, making it a promising option for large reservoirs and other surface-water sources. The integration of PED performance data into an automated processing workflow further demonstrates the potential for real-time quality control and decision support in water supply systems.

At the same time, the results highlight the sensitivity of PED performance to seasonal variations in water quality. When the water conductivity increased from 420–650 µS/cm to around 950 µS/cm, the microbial log-reduction decreased from 7 to approximately 4–5, indicating that changes in conductivity and associated hydrochemical parameters can reduce treatment efficiency. This dependence underscores the need to account for seasonal dynamics in the design and operation of PED systems for large, open water bodies such as the Kapshagay Reservoir.

Despite its technical advantages, PED still faces several limitations. The experiments were performed in a laboratory-scale reactor, and only a limited range of seasonal conditions and microbial indicators was investigated, which constrains direct extrapolation to full-scale operation. In addition, the relatively high capital cost of commercial high-voltage generators and the need for periodic maintenance of electrodes currently increase the overall cost compared with mature technologies like chlorination. These economic and engineering constraints must be addressed before PED can be widely adopted for large-scale water

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treatment.

Future research should therefore focus on pilot-scale and full-scale implementations of PED in continuous-flow reactors directly connected to reservoir intakes, with optimized electrode geometry and pulse parameters to minimize energy consumption and electrode wear. Further work is also needed to investigate combined treatment schemes in which PED is integrated with existing methods (e.g., chlorination or UV) to form a multi-barrier system that reduces chemical doses and by-products. Finally, the development of robust, automated control algorithms linking online measurements of conductivity, turbidity, and microbiological indicators with PED operating regimes will be essential for reliable, cost-effective deployment of this technology in large natural water bodies.

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