

RESEARCH ARTICLE

STUDY OF THE PROCESS OF CLEANING CONTAMINATED GROUNDWATER USING A PILOT UNIT BASED ON ELECTRICAL DISCHARGE

Askar Abdykadyrov^{a,b}, Pavlan Kalandarov^b, Sunggat Marxuly^{a*}, Ainur Kuttybayeva^{a*}, Assel Sankabayeva^c, Mukhit Abdullayev^a, Abdurazak Kassimov^{a,d}, Serikbek Ibekeyev^a, Muratbek Yermekbayev^d

^aDepartment of Electronics, Telecommunications and Space Technologies, Institute of Automation and Information Technologies, Satbayev University, 22 Satbayev street, Almaty, Kazakhstan

^bDepartment of Automation and Control of Technological Processes and Production, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, 39 Kori Niyazi street, Tashkent, Uzbekistan

^cDepartment of Chemical Processes and Industrial Ecology, Mining and Metallurgical Institute named after O.A. Baikonurov, Satbayev University, 22 Satbayev street, Almaty, Kazakhstan

^dDepartment of Telecommunications and Innovative Technologies, Institute of Communications and Aerospace Engineering, Almaty University of Power Engineering and Telecommunications named after G.Daukeev, 126/1 Baytursyov street, Almaty, Kazakhstan

*Corresponding Author Email: sungat50@gmail.com, a.kuttybayeva@satbayev.university

This is an open access journal distributed under the Creative Commons Attribution License CC BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited

ABSTRACT

Article History:

Received 14 March 2025
Revised 12 April 2025
Accepted 28 April 2025
Available online 27 May 2025

This article explores the efficiency of using ozone and electrical discharge methods to remove heavy metals from groundwater. Industrial and agricultural waste contaminates groundwater, leading to high concentrations of heavy metals like Cu, Fe+2, and Fe+3, which pose significant threats to human health and the environment. The objective of this work is to clean contaminated groundwater using an environmentally friendly method that does not require additional chemical reagents. During the study, as the ozone concentration increased from 100 to 500 g/hour and the pH level rose to 7.5, the concentration of Cu ions decreased from 1.20 g/hour to 0.57 g/hour, and Fe+2 reduced from 5.00 g/hour to 0.92 g/hour. The purification efficiency increased with Cu from 75% to 99%, Fe+2 from 35% to 98%, and Fe+3 was entirely removed (100%). Groundwater in Kopa village of the Ayagoz district is characterized by excessive levels of copper ions, and this method demonstrated high effectiveness in addressing the ecological issue. During the purification process, a high sediment yield was observed, significantly improving water quality. The study concludes that ozone and electrical discharge are effective, positioning this method as a promising technology for improving groundwater quality in Kazakhstan and other regions.

KEYWORDS

Electrical discharge, pilot unit, ecological problem, groundwater, purification process, ozone technology.

1. INTRODUCTION

Currently, ecological issues, including groundwater pollution, have become global concerns (Syafiuddin et al., 2020; Abdykadyrov et al., 2023). Contaminated groundwater is one of the major issues when it comes to protecting the environment and human health (Li et al., 2021). Industrial waste, agricultural fertilizers, and household waste degrade water quality, leading to the accumulation of heavy metals and various chemical compounds (Udeigwe et al., 2011). These substances penetrate groundwater, adversely affecting the health of the population that utilizes this resource (Stuart et al., 2012; Abdykadyrov et al., 2024). Scientific research aims to implement environmentally effective and economically viable purification technologies to resolve this issue. Among modern technologies, pilot units based on electrical discharge are emerging as a promising method for water purification. Electrical discharge is considered an effective method for disinfecting water and decomposing heavy metals and organic compounds (Abdykadyrov et al., 2024;

Abdykadyrov et al., 2020). This approach operates on the principle of decomposing pollutants through physical effects rather than chemical processes, thus reducing environmental impact.

This scientific study investigates the possibility of purifying groundwater using a pilot unit based on electrical discharge. The primary advantage of this technology is that it does not require additional chemical reagents, and the purification process is rapid and efficient. Furthermore, this research assesses the effectiveness of the pilot unit and defines its operational limits. The objective of this work is to clean contaminated groundwater using an environmentally friendly method that does not require additional chemical reagents.

2. MATERIALS AND METHODS

The main methods for purifying groundwater affected by ecological issues are as follows (Figure 1).

Quick Response Code	Access this article online	
	Website: www.watconman.org	DOI: 10.26480/wcm.02.2025.356.363

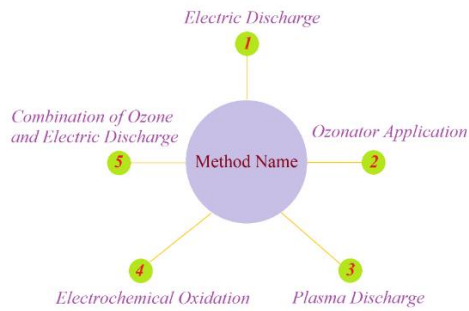
**Figure 1:** Groundwater Purification Methods

Figure 1 presents the primary methods used in groundwater purification. Each method offers different approaches depending on the level of contamination, such as electrical discharge, ozone application, and plasma discharge. The combination of these methods plays a significant role in addressing ecological issues, improving water quality, and eliminating heavy metals and other harmful substances. Efficient use of these methods is a crucial step toward making groundwater environmentally safe and secure (Dai et al., 2020; Thakur et al., 2020; Nyer, 1992). The advantages and disadvantages of these methods can be observed in Table 1 below.

Table 1: Comparative Analysis of Groundwater Purification Methods

Method Name	Efficiency (%)	Energy Consumption (kWh/m ³)	Advantages	Disadvantages
Electric Discharge	85 - 90	3 - 6	Environmentally safe, reagent-free operation	High energy consumption, effectiveness depends on conditions
Ozonator Application	92 - 95	4 - 8	High oxidation capacity, removes organic and metal pollutants	High initial cost of equipment, excess ozone can be hazardous
Plasma Discharge	88 - 93	5 - 10	Removes various pollutants, high effectiveness	Requires high temperatures, equipment wear and tear
Electrochemical Oxidation	80 - 85	2 - 5	Effective in heavy metal removal, reduces water waste	May produce additional harmful compounds, slow process
Combination of Ozone and Electric Discharge	95 - 98	4 - 6	Enhanced efficiency from combining both methods, broad-spectrum purification	High initial investment, requires complex maintenance

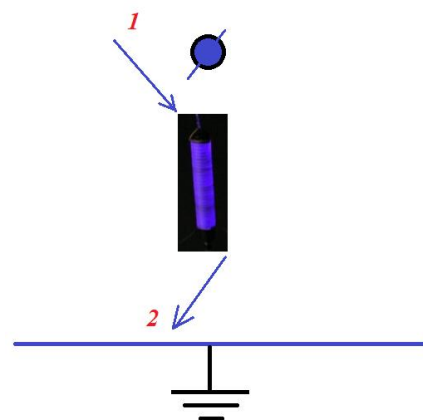
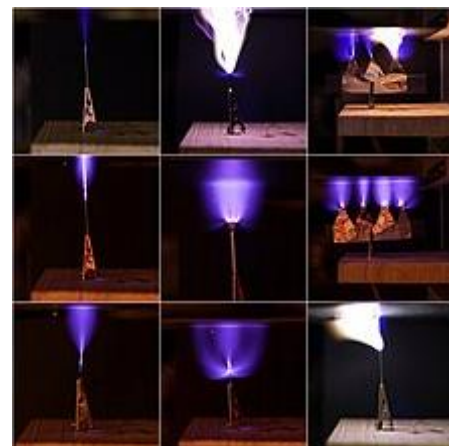
In Table 1, it is evident that the combined method of ozone and electrical discharge demonstrates the highest efficiency (95 - 98%) in groundwater purification, making it the most effective method despite its high initial costs and complex maintenance requirements. The methods of electrical discharge and plasma discharge are also valued for their high pollutant removal efficiency (85 - 93%), although they demand substantial energy, which poses challenges for large-scale applications. Similarly, the electrochemical oxidation method, while slightly lower in efficiency (80 - 85%), stands out for its capability to remove heavy metals with lower energy consumption, making it an environmentally sustainable option for water purification.

Nevertheless, the combination of ozone and electrical discharge remains the recommended approach for groundwater purification, as it achieves the highest efficiency (95 - 98%) and allows for effective removal of a broad range of contaminants. However, when selecting this method, it is important to consider the high initial investment and the need for complex technical maintenance. If reducing initial costs and simplifying maintenance are priorities, electrochemical oxidation is also worth considering due to its efficient removal of heavy metals and relatively lower energy consumption.

2.1 Theoretical Analysis of the Properties of Electrical Discharge

In our scientific research, special attention was given to corona discharge within the scope of electrical discharge. Corona discharge is a weakly glowing gas discharge that occurs at atmospheric or near-atmospheric pressure. For corona discharge to occur, the voltage across the electric field must be significantly non-uniform, which arises from the small radius curvature of the corona. This condition—high non-uniformity of the electric field—can be achieved in various electrode systems (Abdykadyrov et al., 2021; Abdykadyrov et al., 2020).

In this study, two electrode systems were examined. In the first system, the electrode with a pointed tip creates a high electric field gradient, while the other electrode is a flat surface. In the second system, which has an axial structure, a high electric field gradient is generated at the central electrode, typically made of a thin wire. The second electrode is a conductive cylinder. A distinctive feature of corona discharge is the presence of two zones (Figure 2). In the first zone, ionization processes occur near the electrode with lower curvature and a high voltage gradient. This zone is known as the "active" or "ionization zone" or the "sheath" of the corona. The size of this region is significantly smaller than the overall discharge gap.

**Figure 2:** Negative Corona in Air. In this context: 1 – ionization zone, 2 – outer zone. $U = 20$ kV, $d = 25$ mm.

In the second zone, ionization processes do not occur; instead, a charge transport process takes place. This zone is referred to as the "outer zone." The discharge current is determined by the self-sustained volumetric charge created in the ionization zone, which fills the outer region. In all types of corona discharges, the potential gradient at the corona electrode

remains constant across a wide range of discharge currents, differing only slightly from the initial field gradient at the onset of discharge. Since the discharge current is defined by the self-sustained volumetric charge, studying corona discharges involves examining the distribution of the electric field, potential distribution, concentration distribution of charge carriers, energy distribution of electrons and ions, as well as the processes of ionization and recombination.

Currently, various types of corona discharges are subjects of specific studies. Depending on the polarity of the voltage applied to the corona electrode, the corona can be either positive or negative.

Positive Corona. In positive corona discharge, a high positive voltage is applied to a small-diameter wire or pointed electrode, while a larger diameter cylinder or plate is grounded. When the ignition voltage is reached, free electrons that appear in the space between the electrodes accelerate toward the electrode with the positive potential. In the ionization zone, which is located very close to the corona electrode, positive ions and electrons are formed through elastic collisions between electrons and neutral gas molecules. In dry air, O_2^+ and N_2^+ ions dominate. The newly generated free electrons are accelerated by the electric field, causing further ionization, which takes on an avalanche effect.

To sustain the discharge, secondary electrons are generated in the gas through photoionization, which is facilitated by photons emitted during recombination processes in the plasma region. In Yu.P. Raizer's research [14], the criterion for the onset of positive corona is considered to be the formation of a streamer under conditions of a non-uniform electric field.

$$\int_0^{x_1} (\alpha - a) dx \approx 18 - 20 \quad (1)$$

Here, α represents the ionization coefficient, and a denotes the attachment coefficient.

Unlike the stable glow of a negative corona, positive corona discharges exhibit streamers, which appear as luminous threads radiating from the tip. The plasma zone in the corona is primarily defined as a region dominated by electron reactions. In the positive corona, the plasma zone corresponds to the ionization region. If the field intensity E_k at the corona electrode exceeds a specific threshold, a self-sustained corona discharge occurs. The initial corona ignition voltage U is related to the required field intensity E_k .

The first empirical formula for determining the critical field required for corona ignition between coaxial cylinders was proposed by F. Peek [15].

$$E_k = 31\delta \left(1 + \frac{0.308}{\sqrt{r\delta}} \right) \text{ kV/cm} \quad (2)$$

where δ is the ratio of air density to standard conditions, i.e., $p = 760$ torr, $t = 25^\circ\text{C}$; r is the radius of the inner electrode in centimeters; and E_k is in units of V/m. The initial field intensity can be determined through calculations based on the condition for self-sustained discharge, which can be expressed as follows:

$$\int_{S_0}^{S_k} \alpha_{\text{effective}} ds = K_1 \quad (3)$$

Here, K_1 is a constant characterizing secondary ionization processes, and $\alpha_{\text{effective}}$ is the effective ionization coefficient. For air, the dependence of the effective ionization coefficient on the field intensity is approximated by the following expression:

$$\alpha_{\text{effective}} = a\delta \left(\frac{E}{c} - c \right)^2 \quad (4)$$

where a and c are constant coefficients. An expression was derived for the discharge intensity in an air gap with a constant field, and the values of these coefficients were determined by comparison with experimental values of discharge intensities: $c = 24.5 \cdot 10^5 \text{ V/m}$, $\sqrt{K_1/\alpha} = 6.5 \cdot 10^4 \text{ V/m}^{1/2}$

In Yu.P. Raizer's research [14], expressions for the electric field intensity under certain conditions are provided. When the radii of the concentric spheres are r and R , the field intensity is given by:

$$E = \frac{V_r R}{x^2(R-r)}, E_{\text{max}} \approx \frac{V}{r} \quad (\text{where } R \gg r) \quad (5)$$

Between a sphere and a distant plane ($R/r \rightarrow \infty$) $E \approx V_r/x^2$. For a parabolic-shaped tip with a curvature radius r and a perpendicular distance d from the tip to the plane, at a distance x along the extension of its axis:

$$E = \frac{2V}{(r+2x)\ln\left(\frac{2d}{r}\right)}, E_{\text{max}} \approx \frac{2V}{r \ln\left(\frac{2d}{r}\right)} \quad (6)$$

The maximum field between parallel wires located at a distance b from each other, at a height d from the ground, is given by:

$$E_{\text{max}} \approx \frac{V}{r \ln\left[b/r\sqrt{1+(b/2d)^2}\right]} \quad (7)$$

For a single wire above a plane ($b \rightarrow \infty$) and for two wires in free space ($d \rightarrow \infty$), we obtain the following expressions, respectively:

$$E_{\text{max}} \approx \frac{V}{r \ln\left(\frac{2d}{r}\right)}, E_{\text{max}} \approx \frac{V}{r \ln\left(\frac{b}{r}\right)} \quad (8)$$

Free electrons also attach to electronegative gas molecules (such as O_2), forming negative ions, or they recombine with positive ions. Since recombination coefficients are low and charge density is relatively low, recombination is usually negligible. As a result, ionization primarily competes with electron attachment. Near the high positive potential electrode, ionization prevails over the attachment of newly generated electrons. At distances of several wire radii beyond the outer boundary of the corona plasma, the ionization rate equals the rate of electron attachment. All newly generated electrons attach to molecules, forming negative ions. Outside the corona plasma region, the field intensity is insufficient to create electrons. In this zone, ions with the same polarity as the discharge electrode move toward the grounded electrode. Positive ions carry the entire current outside the active ionization region.

The primary parameter of corona discharge is its volt-ampere characteristic (VAC). The average VAC of corona discharge can be approximated by a parabolic expression with acceptable precision for practical purposes.

$$I = kV(V - V_0) \quad (9)$$

where I is the corona current, V is the voltage between the electrodes, k is a dimensional coefficient related to the geometry of the electrodes and the mobility of charge carriers in the corona drift region, and V_0 is the initial corona voltage. From this expression, it can be seen that the corona can only exist at voltages above the ignition voltage, meaning $V > V_0$. It is understood from expression (9) that currents in the sub-nanoampere range up to the initial corona voltage are not considered here. Numerous studies have refined the analytical expression for the volt-ampere characteristic of corona discharge, with research on this subject dating back to the 1950s (Sun et al., 2023; Shreve., 1951).

Negative Corona. When the corona electrode is connected to the negative pole of the power source, a negative corona discharge occurs. The primary process that sustains the current in the cathode layer is the avalanche multiplication of electrons. Secondary processes include emission from the cathode and photoionization in the gas volume. The formation of electron avalanches is similar to the process in positive corona. In Yu.P. Raizer's monograph a criterion for the ignition of a negative corona is provided (Raizer, 1970):

$$\int_0^{x_1} [\alpha(x) - a(x)] dx = \ln(1 + \gamma^{-1}) \quad (10)$$

where α is the ionization coefficient, a is the attachment coefficient of electrons, and γ is the effective coefficient of secondary emission. Secondary electrons are generated through photoemission from the surface of the high-potential electrode.

Theoretically, secondary electrons in a negative corona can be obtained either through bombardment of the discharge electrode by positive ions or through photoionization of the gas. In corona plasma, the average kinetic energy of ions is approximately 0.01 - 0.1 eV, which is insufficient to eject electrons from the electrode surface. However, photons emitted in the active region of the corona discharge have enough energy to ionize gas particles and release electrons from the electrode surface. Since the work function (approximately 4 or 5 eV) for metals is much lower than the ionization energy of oxygen and nitrogen molecules (12.06 eV for O_2 and 15.6 eV for N_2), the number of photoelectrons emitted from the electrode surface is significantly higher than that from the gas. Thus, the generation of secondary electrons primarily occurs through photoemission from the surfaces of the discharge electrodes.

The number of photoelectrons depends on the wavelength of the photons

and the work function of the discharge electrode material. As with positive corona, the volt-ampere characteristic (VAC) of negative corona may depend on the electrode material and surface condition. In the corona sheath, the creation of new electrons through electron impact ionization exceeds the attachment of electrons to O₂. As in positive corona, the ionization rate decreases to match the electron attachment rate at the ionization boundary as the electric field weakens. Beyond the ionization boundary, attachment surpasses ionization, gradually reducing the number of free electrons and weakening the electric field.

The volt-ampere characteristic of the negative corona resembles that of the positive corona and can be adequately approximated by expression (9) in practice (Wu et al., 2020; Liang et al., 2014).

3. RESULTS AND DISCUSSIONS

From the previous section on materials and methods, it is evident that combining ozone and electrical discharge is the optimal method for purifying groundwater, considering the properties of electrical discharges. To this end, we decided to conduct a scientific research project at the Department of Electronics, Telecommunications, and Space Technologies at the Kazakh National Research Technical University named after K.I. Satbayev. The study’s objective is to focus on purifying groundwater in the Kopa village of the Ayagoz district, located in the eastern territory of Kazakhstan. This area is impacted by copper mining and processing activities in Aktogay, which is situated 7 kilometers from Kopa. The large-scale processing of sulfide ore, in particular, could have ecological consequences on the quality of underground drinking water.

With an annual production of 77.3 million tons of ore, including 58.6 million tons of sulfide ore, the significant production volume has considerable environmental impact. Contaminants, such as heavy metals and chemical compounds released during sulfide ore processing, seep into the ground and increase the risk of contamination of water sources. This risk is further heightened by the annual processing of up to 54.3 million tons of sulfide ore, which involves high temperatures and the use of chemical reagents. Additionally, with a 12% increase in copper production, the spread of heavy metals into groundwater has also risen, raising concerns about the contamination of drinking water sources. The schematic of the production area is shown in Figure 3 below.

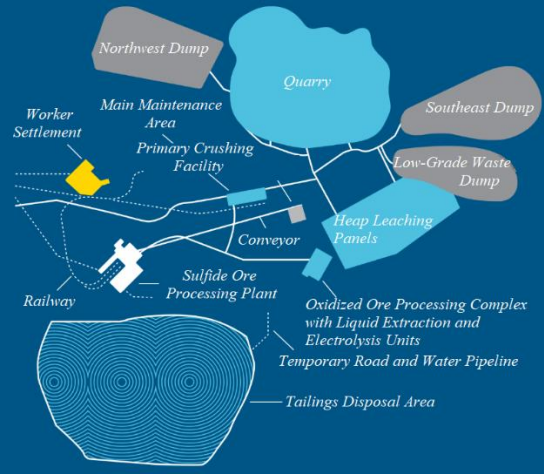


Figure 3: Production Site Layout (KAZ Minerals, 2024)

Information on the main resources of the production project, namely electric power, water resources, transport infrastructure, and labor resources, is provided in Table 2 below.

Table 2: Main Resources of the Production Project.	
	Electric Power A 220 kV transmission line from the Karaganda power station Competitive cost of electricity.
	Water Resources Water supply from groundwater extracted from underground wells The enrichment plant will reuse 70-80% of the technical water.
	Transport Infrastructure Railway branch connected to the national railway network Loading of ore bags directly into wagons in the packaging workshop Two days' travel to Alashankou station at the China border.
	Labor Resources 1,500 employees Transfer of management functions to local specialists after project launch.

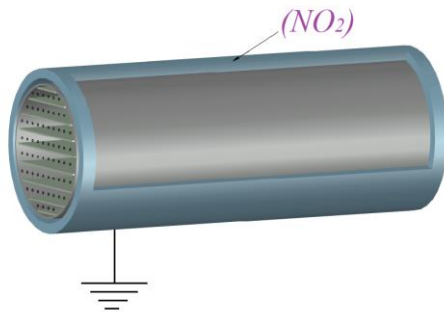
The composition of groundwater within a 5 – 6-meter radius around the production site is provided in Table 3 below.

Table 3: Potential Contaminants in Groundwater Near Copper Processing Sites and Their Environmental Impact					
Compound Name	Composition	Potential Source of Pollution	Initial Concentration in Groundwater (mg/L)	MAC (mg/L)	Hazard and Impact
Copper ions (Cu ²⁺)	Copper sulfides	Emission from copper processing	1,3	1,0	Pollutes water systems, has toxic effects
Sulfate ions (SO ₄ ²⁻)	Sulfur ore and waste	Acid treatment of sulfide ores	5,0	250	Can increase water acidity
Iron ions (Fe ²⁺ /Fe ³⁺)	From iron sulfides	Produced through acidic oxidation	5,3 - 0,7	0,3	Changes water color, harmful impact
Arsenic (As)	From sulfide minerals	Released as a byproduct	0,001	0,01	Toxic, hazardous to human health
Cadmium (Cd)	Mineral component in ores	Pollution as a secondary component	0,0002	0,005	Carcinogenic, causes chronic diseases
Zinc (Zn)	Zinc sulfides	Emitted in sulfide ore processing	0,28	5,0	Pollutes water sources, poses environmental risk
Lead (Pb)	Lead ores	May remain as waste in acidic conditions	0,003	0,01	Harmful to the human nervous system

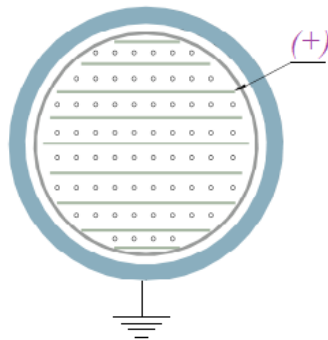
Table 3 (Cont.): Potential Contaminants in Groundwater Near Copper Processing Sites and Their Environmental Impact

Sulfide ions (S^{2-})	Sulfide ores	Direct discharge and as residual waste	0,02	0,05	Increases water acidity, transports heavy metals
Aluminum (Al^{3+})	Waste from ore enrichment	Released during processing	0,05	0,2	Dissolves in acidic water, harmful to plants
Manganese (Mn^{2+}/Mn^{3+})	May be present in ores	Heavy metal emissions and waste	0,02	0,1	Pollutes water sources, environmental threat

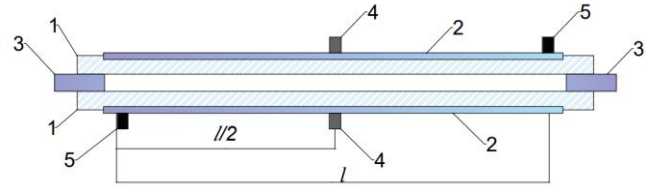
From this table, it can be observed that copper ions (Cu^{2+}) and iron ions (Fe^{2+}/Fe^{3+}) exceed the maximum permissible concentration (MPC). To address this issue and conduct research, a specialized setup based on electrical corona discharge was developed in the department. The general laboratory setup and structural diagrams of the equipment can be seen in Figures 4a, b, c, and d below.



a) Side View of the Ozonator



b) Front View of the Ozonator



c) Structure of the Ozonator



d) Laboratory Model

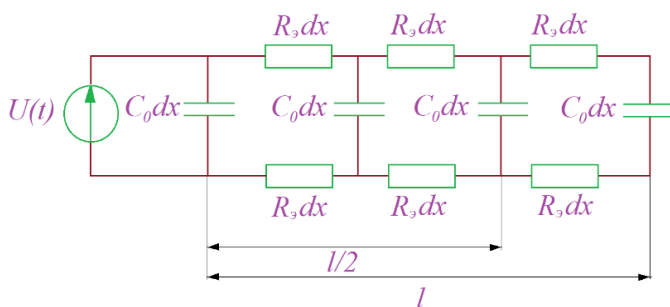
Here: 1 – Cooling system gap between the two electrodes; 2 – Dielectric material made of fluoroplastic; 3 – Stopper made of fluoroplastic material; 4 – Tube supplying water or transformer oil to the cooling system; 5 – Tube supplying air or oxygen; l – Length of the ozonator.

Figure 4: Structural Image of the Ozonator Unit Based on Electrical Corona Discharge

The technical specifications of the laboratory setup shown in Figure 4 can be found in Table 4 below.

Table 4: Technical Specifications of the Laboratory Ozonator

Input Voltage (Network Voltage)	Voltage Supplied to the Ozonator	Ozone Output	Unit Dimensions	Unit Weight	Max. Noise Level	Timer
220V, 50Hz	10 - 21 kV	120 g/h	1000 x 150 x 125 mm	5 kg	15 dB	from 5 to 60 minutes

**Figure 5:** Electrical Circuit for Voltage Amplification in the Ozonator

In some scientific studies, the mathematical model of barrier microdischarge is presented within a distributed-parameter electrical circuit (Kozhaspaev et al., 2016; Bagdollaulay et al., 2024). Additionally,

ozone generation systems in the barrier consider the absence of active resistance in highly conductive electrodes. The proposed research study takes into account the active resistance of the electrodes. Thus, for ozone generation systems and the electrical circuit in Figure 5, the primary equations can be defined as follows:

$$\frac{\partial u(x,t)}{\partial x} + (R_p + R_3) \cdot i(x,t) = 0 \quad (11)$$

$$\frac{\partial^2 u(x,t)}{\partial x^2} - (R_p + R_3) \cdot C_0 \frac{\partial u(x,t)}{\partial t} = 0 \quad (12)$$

where $u(x,t)$ represents the distribution of the voltage drop across the resistance at any time t . Parabolic-type equations, such as equation (12), are typically used to describe heat conduction and diffusion processes and are also applied in electrical energy transmission (Bataklijev et al., 2014). The phase transition approach is most suitable for describing the avalanche ionization process in gas discharge. Here, there is a change in the

physical state of the substance. In our case, the ionized state of low-temperature plasma transitions to a weakly ionized state during discharge and ionization.

In mathematical physics, phase transition problems are associated with changes in the temperature of the substance. With the development of electrical discharge, the phase state is defined by the transition from a weakly ionized state to a plasma state. The threshold value of the electric field intensity, E_0 , in the discharge region is significantly enhanced due to ionization effects in this area.

3.1 Decomposition of Ozone in Water

The decomposition of ozone in both surface and groundwater is generally described by a first-order kinetic equation. This research was tested using the ETRO-02 ozonator unit, which is based on laboratory electrical corona discharge. The overall technological diagram of the setup is shown in Figure 6 below.

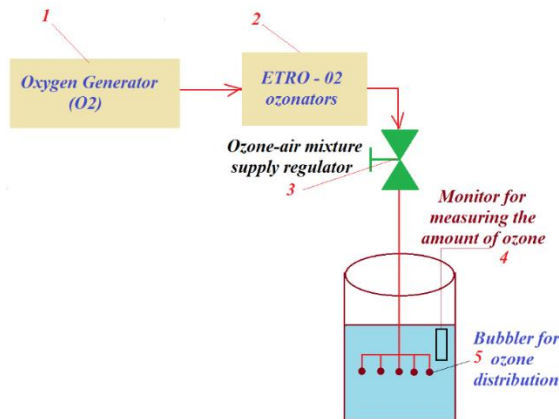
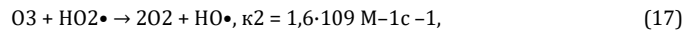
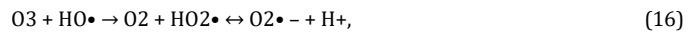
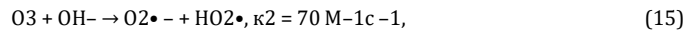
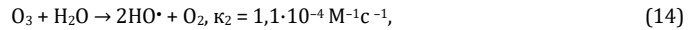


Figure 6: Technological Diagram of the Laboratory Model

$$-\left(\frac{d[O_3]}{dt}\right)_{pH} = k^* [O_3] \quad (13)$$

This process proceeds through the following reactions (Raizer, 1970):



The reactions presented in expressions (13 - 18) describe the kinetics of ozone decomposition in aqueous solutions. Each of these reactions demonstrates how ozone (O_3) decomposes under specific conditions, such as in an alkaline environment (with a high concentration of OH^- ions). The k values next to each reaction represent the reaction rate constants, which characterize the rate of reaction per second, indicating the efficiency of each reaction over time.

3.2 Experimental Studies Based on Scientific Research

The experimental studies were conducted focusing on the chemical composition of the water. This is because the groundwater used in this locality fully meets the microbiological standards of GOST-2874-82. In other words, the water quality satisfies the maximum allowable concentrations for its biological composition. However, the presence of certain heavy metal ions in the water does not comply with the mentioned standard. The initial water composition, which shows copper (Cu^{2+}) and iron (Fe^{2+}/Fe^{3+}) ion levels exceeding the MAC requirements, is presented in Table 5 below.

Table 5: The amount of copper (Cu^{2+}) and iron (Fe^{2+}/Fe^{3+}) ions that do not meet the Maximum Allowable Concentration (MAC) requirements based on the initial water composition

Compound Name		Composition	Potential Source of Pollution	Initial Concentration in Groundwater (mg/L)	MAC (mg/L)	Hazard and Impact
Copper ions (Cu^{2+})		Copper sulfides	Emission from copper processing	1,3	1,0	Pollutes water systems, has toxic effects
Iron ions (Fe)	Fe^{2+}	From iron sulfides	Produced through acidic oxidation	5,3	0,3	Changes water color, harmful impact
	Fe^{3+}			0,7		

During the scientific research, it was observed that the oxidation of iron (Fe^{2+}/Fe^{3+}) and copper (Cu^{2+}) in water, using an ozone-air mixture and oxygen from the air, proceeds intensely within the first 15 minutes, after which the oxidation rate decreases. The results of these studies can be seen in Tables 6 and 7 below.

Table 6: Oxidation of Harmful Compounds Based on Ozone Amount

Compound Name	pH hydrogen index	Ozone Amount, g/hour (with a constant treatment time during the experiment, $t = 20$ minutes)							
		100	200	300	400	500	600	700	800
Copper ions (Cu^{2+})	6,5 – 7,5	1,20	1,15	1,00	0,85	0,57	-	-	-
Iron ions Fe^{2+}		5,00	4,25	3,18	2,33	1,00	0,92	-	-
Iron ions Fe^{3+}		0,68	0,55	0,37	0,28	0,17	-	-	-

Table 6 highlights the oxidation process of harmful compounds based on varying ozone concentrations, with the pH held between 6.5 and 7.5. For copper ions (Cu^{2+}), the concentration gradually decreases from 1.20 g/hour at 100 g/hour of ozone to 0.57 g/hour at 500 g/hour, showing effective oxidation as ozone levels increase. Iron ions in Fe^{2+} form also

decrease consistently, starting from 5.00 g/hour at 100 g/hour of ozone to 0.92 g/hour at 600 g/hour, indicating higher reactivity compared to copper ions. Iron ions in Fe^{3+} show a rapid reduction, from 0.68 g/hour at 100 g/hour of ozone to 0.17 g/hour at 500 g/hour, confirming effective oxidation at lower ozone levels.

Table 7: Results of Wastewater Ozone Treatment and Purification Efficiency							
pH hydrogen index	Concentration in solution after ozone treatment, mg/dm ³			Sediment yield, g/dm ³	Wastewater purification degree, %		
	Cu	Fe ⁺²	Fe ⁺³		Cu	Fe ⁺²	Fe ⁺³
6,5	1,3	5,3	0,7	5,48	75	35	97
6,8	1,0	4,85	0,45	6,3	76	46	99
7,0	0,98	3,75	-	7,87	97	75	100
7,2	0,75	1,2	-	8,1	98	90	100
7,5	0.5	0,12	-	9,5	99	98	100

This table describes the parameters of wastewater following ozone purification. For example, depending on the pH level, copper removal efficiency reached 75% to 99%. Iron (Fe²⁺ and Fe³⁺) levels decreased from an initial 5.3 mg/dm³ to 0.12 mg/dm³, with purification efficiency increasing from 35% to 100%.

Thus, ozone treatment could potentially be used in the future for the removal of certain heavy metal salts from technological solutions in groundwater. It was observed that, within 1 hour of ozone treatment, metal concentrations dropped to <0.01 mg/L, below the maximum allowable concentration (MAC) for metals in water. Overall, the results of this scientific study reduce the environmental impact, offering a more ecologically sustainable purification solution.

3.3 Analysis of Experimental Results

This research on groundwater purification using ozone is relevant due to the increasing need for effective methods to remove heavy metals, as they pose significant risks to health and the environment. The study demonstrated that controlling the pH level during ozone-based purification significantly enhances the removal efficiency of harmful metal ions such as Cu, Fe²⁺, and Fe³⁺. As the demand for clean water continues to grow, this method offers an efficient and accessible solution for reducing the concentration of toxic metals in groundwater. By optimizing sediment yield and purification efficiency, the study addresses both economic and environmental aspects, supporting a more sustainable purification process.

Therefore, this research contributes to advancements in water purification technology and aligns with global efforts to improve water safety and quality. The experimental results are illustrated in Figures 7, 8, and 9 below.

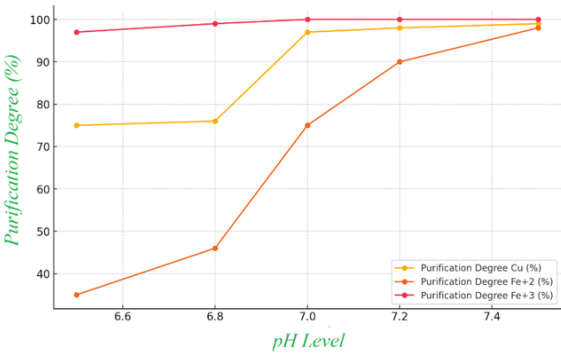


Figure 9: Wastewater Purification Efficiency by Metal Type and pH Level

The scientific results obtained from the experiment can be summarized as follows:

- **Concentration of Metals After Ozone Treatment:** As the pH level increases from 6.5 to 7.5, the concentration of copper (Cu) in the solution decreases from 1.3 mg/dm³ to 0.5 mg/dm³. Similarly, Fe+2 shows a significant reduction from 5.3 mg/dm³ to 0.12 mg/dm³, and Fe+3 decreases sharply until it is no longer detected at pH 7.0 and above, indicating effective metal removal at higher pH levels;
- **Sediment Yield by pH Level:** The sediment yield rises steadily as the pH increases, starting from 5.48 g/dm³ at pH 6.5 to 9.5 g/dm³ at pH 7.5. This increase indicates more effective coagulation and sedimentation of contaminants with higher pH values, enhancing the efficiency of wastewater treatment;
- **Purification Efficiency by Metal Type and pH Level:** The purification degree for Cu increases from 75% at pH 6.5 to 99% at pH 7.5, while Fe+2 improves from 35% to 98%. Fe+3 reaches near-complete purification at 97% initially and achieves 100% removal by pH 7.0, showing that higher pH levels contribute significantly to the purification process for all metals.

4. CONCLUSION

This research evaluated the effectiveness of combining ozone and electrical discharge for purifying groundwater affected by environmental contamination. Groundwater purification has become an important issue today, as industrial and agricultural waste degrades water quality and leads to the accumulation of heavy metals. In the purification process, as the amount of ozone increased and oxidation levels rose from 100 g/hour to 500 g/hour, the concentration of Cu²⁺ dropped from 1.20 g/hour to 0.57 g/hour. Similarly, Fe²⁺ concentrations decreased from 5.00 g/hour to 0.92 g/hour, and Fe³⁺ reduced from 0.68 g/hour to 0.17 g/hour, enhancing the efficiency of the purification process. Sediment yield increased, reaching 9.5 g/dm³ at a pH of 7.5, ensuring water cleanliness.

Moreover, purification efficiency for copper (Cu) rose from 75% to 99%, for iron (Fe²⁺) from 35% to 98%, and for Fe³⁺, the purification level reached 100% from an initial 97%. In Kopa village of the Ayagoz district, the initial copper ion concentration in groundwater was 1.3 mg/dm³, exceeding the maximum allowable concentration (MAC), making it essential to apply an effective purification method. As a result, the proposed method is environmentally friendly and efficient, as it does not require additional chemical reagents. This study demonstrated that ozonation can reduce metal ion concentrations below MAC levels, ensuring safe water quality.

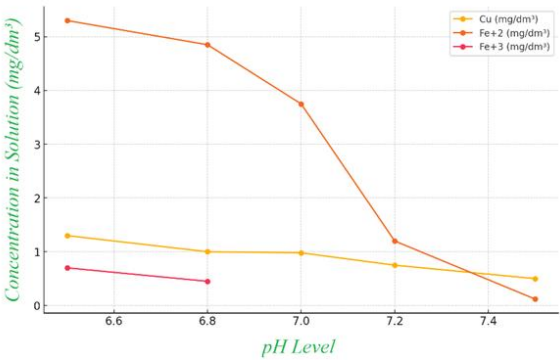


Figure 7: Concentration of Metals After Ozone Treatment

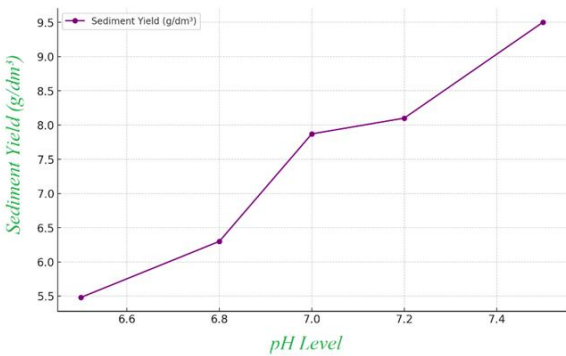


Figure 8: Sediment Yield vs pH Level after Ozone Treatment

Furthermore, the findings support global environmental goals to protect water resources by showing that this method can be used on a larger scale. It will be valuable to evaluate this method's effectiveness for other heavy metals and contaminants. This approach offers a practical means to improve environmental conditions, particularly in areas with high heavy metal concentrations. The sediment produced during the process further contributes to the effective removal of pollutants, indicating that combining ozone and electrical discharge can address ecological challenges in groundwater purification.

These results point to promising directions for implementing effective technologies to counter groundwater pollution. Using high pH and ozone concentrations enabled the complete removal of heavy metals and increased sediment yield. Continued development of this approach could lead to scientific and practical recommendations aimed at enhancing groundwater quality in Kazakhstan and other regions.

REFERENCES

- Abdykadyrov, A. A., Korovkin, N. V., Mamadiyarov, M. M., Tashtay, Y., and Domrachev, V. N., 2020, March. Practical research of efficiency of the installation Etro-02 ozonizer based on the corona discharge. In 2020 International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Pp. 1-5. IEEE.
- Abdykadyrov, A. A., Korovkin, N. V., Mamadiyarov, M. M., Tashtay, Y., and Domrachev, V. N., 2020, March. Practical research of efficiency of the installation Etro-02 ozonizer based on the corona discharge. In 2020 International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Pp. 1-5. IEEE.
- Abdykadyrov, A. A., Korovkin, N. V., Tashtai, E. T., Syrgabaev, I., Mamadiyarov, M. M., and Sunggat, M., 2021, March. Research of the process of disinfection and purification of drinking water using ETRO-02 plant based on high-frequency corona discharge. In 2021 3rd International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Pp. 1-4. IEEE.
- Abdykadyrov, A., Abdullayev, S., Tashtay, Y., Zhunussov, K., and Marxuly, S., 2024. Purification of surface water by using the corona discharge method. *Mining of Mineral Deposits*, 18(1), Pp. 125-137.
- Abdykadyrov, A., Kalandarov, P., Taissariyeva, K., Marxuly, S., Abdykadyrkyzy, R., Kassimov, A., and Yerzhan, A., 2024. Study of the process of neutralizing and oxidizing harmful phenol compounds in wastewater using ozone technology. *Water Conservation & Management (WCM)*, 8(4), Pp. 420-429.
- Abdykadyrov, A., Marxuly, S., Mamadiyarov, M., Smailov, N., Zhunusov, K., Kutybaeva, A., and Orazbekov, A., 2023. Investigation of the Efficiency of the Ozonator in the Process of Water Purification Based on the Corona Discharge. *Journal of Ecological Engineering*, 24(2), Pp.140-151.
- Bagdollauly, Y., Yerkeldessova, G., Oralbekova, A., Chukenova, E., Ilyassov, N., Yerzhan, A., and Kalandarov, P., 2024, August. Investigation of the properties of electrical sources of ozonators through mathematical models. In IOP Conference Series: Earth and Environmental Science (Vol. 1390, No. 1, Pp. 012021. IOP Publishing.
- Batakliev, T., Georgiev, V., Anachkov, M., Rakovsky, S., and Zaikov, G. E., 2014. Ozone decomposition. *Interdisciplinary toxicology*, 7(2), Pp. 47.
- Dai, Y., Liu, M., Li, J., Yang, S., Sun, Y., Sun, Q., and Liu, Z., 2020. A review on pollution situation and treatment methods of tetracycline in groundwater. *Separation science and technology*, 55(5), Pp. 1005-1021.
- KAZ Minerals, 2024. The scheme of the production site <https://www.kazminerals.com/ru/%D0%B3%D0%BB%D0%B0%D0%B2%D0%BD%D0%B0%D1%8F/our-business/aktogay/>
- Khan, M. S., Ahmad, S., Shah, Z., Alshehri, A., Vrinceanu, N., and Garalleh, H. A., 2024. Computational study of double diffusive MHD natural convection flow of non-Newtonian fluid between concentric cylinders. *Results in Engineering*, 21, 101925.
- Kholikulov, D. B., and Matkarimov, S. T., 2021. Pilot tests of processing technologies of process solutions of copper production by ozonation. *Materials Today: Proceedings*, 45, Pp.4987-4992.
- Kozhaspaev, N. K., Makanov, U., Bokanova, A. A., Abdykadyrov, A. A., Dagarbek, R., and Kodzhavergenova, A. K., 2016. Experience in application of ozonic technology for sewage treatment in the Kumkul region of Kazakhstan. *Journal of Industrial Pollution Control*, 32(2), Pp. 486-489.
- Li, P., Karunanidhi, D., Subramani, T., and Srinivasamoorthy, K., 2021. Sources and consequences of groundwater contamination. *Archives of environmental contamination and toxicology*, 80, Pp.1-10.
- Liang, T., Jiang, X., Wang, Z., Sun, F., Cong, P., and Qiu, A., 2014. Characteristics study of multigaps gas switch with corona discharge for voltage balance. *IEEE Transactions on Plasma Science*, 42(2), Pp.340-345.
- Nyer E. K., 19992. Groundwater treatment technology. – John Wiley & Sons, 1992. https://books.google.kz/books?hl=ru&lr=&id=KL0XxExwX86sC&oi=fnd&pg=PP9&dq=Groundwater+treatment+methods&ots=Z9zaGEmEp2&sig=VKLIVXnJqDfrzPzP99gcO7Oq4&redir_esc=y#v=onepage&q=Groundwater%20treatment%20methods&f=false
- Raizer, Y. P., 1970. High-Frequency High-Pressure Induction Discharge And Theelectrodeless Plasmotron. *Soviet Physics Uspekhi*, 12(6), Pp. 777.
- Shreve Jr, J. D., 1951. A dynamic method for obtaining volt-ampere characteristics of probes in electrical gas discharges. *Lehigh University*.
- Stuart, M., Lapworth, D., Crane, E., and Hart, A., 2012. Review of risk from potential emerging contaminants in UK groundwater. *Science of the Total Environment*, 416, Pp.1-21.
- Sun, Z., Shao, Z. K., Sun, X., and Sun, W. F., 2023. Trichel pulse characteristics and mechanism of negative corona discharge in sub-millimeter gaps. *Physics of Plasmas*, 30(6).
- Syafiuddin A., Boopathy R., Hadibarata T., 2020. Challenges and solutions for sustainable groundwater usage: Pollution control and integrated management //Current Pollution Reports.2020, 6, Pp. 310-327. DOI<https://doi.org/10.1007/s40726-020-00167-z>
- Thakur, A. K., Vithanage, M., Das, D. B., and Kumar, M., 2020. A review on design, material selection, mechanism, and modelling of permeable reactive barrier for community-scale groundwater treatment. *Environmental Technology & Innovation*, 19, 100917.
- Udeigwe, T. K., Eze, P. N., Teboh, J. M., and Stietiya, M. H., 2011. Application, chemistry, and environmental implications of contaminant-immobilization amendments on agricultural soil and water quality. *Environment international*, 37(1), Pp. 258-267.
- Wu, Y., Lei, L., Zhang, J., Ge, D., and Zhang, J., 2020, February. Analysis of current characteristics of corona discharge in high voltage transmission. In IOP Conference Series: Earth and Environmental Science (Vol. 440, No. 3, p. 032040). IOP Publishing.

