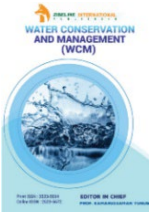
ZIBELINE INTERNATIONAL™
PUBLISHING

Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.01.2025.40.48

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD



RESEARCH ARTICLE

STUDY OF THE WASTEWATER TREATMENT PROCESS USING ELECTRICAL DISCHARGE

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ARTICLE DETAILS

Article History:

Received 18 October 2024
Revised 20 November 2024
Accepted 12 December 19 2024
Available online 29 January 2025

ABSTRACT

This research focuses on studying the process of wastewater treatment using electrical discharge. The introduction highlights the harmful effects of ammonia, nitrites, phosphates, and heavy metals found in wastewater and their impact on water pollution. The purpose of the study is to investigate and evaluate the efficiency of decomposing harmful substances in water using ozone and hydroxyl radicals generated by high- and low-frequency electrical discharges. During the experiment, a voltage of 15 kV and an ozone concentration of 600 g/h were applied. The results showed that the initial ammonia concentration decreased from 130 mg/L to 1 mg/L, while nitrites were reduced from 0.5 mg/L to 0 mg/L. In addition, phosphates (from 30 mg/L to 0 mg/L), chlorides (from 250 mg/L to 20 mg/L), and sulfates (from 200 mg/L to 18 mg/L) significantly decreased. The COD level dropped by 70%, from 800 mg/L to 0 mg/L, and the bacterial count decreased by 85% within 30 minutes, reaching 100% elimination by 60 minutes. The energy consumption was 0.5 kWh per liter of water, proving this method to be an efficient and environmentally friendly solution. The conclusion highlights the potential of the electrical discharge method for water purification without chemical additives, its environmental safety, and its applicability on an industrial scale.

KEYWORDS

Wastewater treatment, electrical discharge, contaminant decomposition, high-frequency electric field, chemical oxygen demand (COD), bacterial elimination, environmental safety, sustainable technology

1. INTRODUCTION

Wastewater treatment using electrical discharge is one of the promising methods aimed at addressing environmental issues (Saravanan, et al., 2021). Effluents from many industrial facilities and household waste contain high levels of chemical pollutants, bacteria, and viruses that harm ecosystems (Gurreri et al., 2020; Kozhaspaev et al., 2016). Such contaminated water poses a significant threat to ecosystems, reducing biodiversity in water sources and negatively impacting the environment. Today, protecting water sources, recycling, and maintaining them in an environmentally safe state has become a crucial task (Cosgrove and Loucks ., 2015).

Treatment through electrical discharge is a modern technology that uses a high-frequency electric field to decompose contaminants in water (Abdykadyrov et al., 2021). As a result of the electric discharge, ozone, hydrogen peroxide, and other strong oxidants are formed, which break down harmful substances in the water. This process turns heavy metals, bacteria, and organic substances in the water into harmless components, resulting in ecologically clean water (Abdykadyrov et al., 2020).

One of the unique features of treatment through electrical discharge is its ability to reduce pollution without the use of chemical additives. The environmental safety of this technology is one of its main advantages, as no additional chemical substances are introduced into the water. Therefore, it provides efficient cleaning without harming the environment. Economically, it is also advantageous, as water treatment can be achieved by using only electrical energy, without the cost of additional chemicals (Ahmed et al., 2021; Abdykadyrov et al., 2023)

This method is currently used in many countries to comply with environmental standards. Researchers are studying ways to adjust various parameters, such as voltage, frequency, and temperature, to increase the effectiveness of electrical discharge. These studies contribute significantly to ensuring water's environmental cleanliness, protecting human health, and preserving water resources. Furthermore, the potential for industrial-scale application of this technology is being explored, as it is easily scalable and considered effective in many cases (Anpilov et al., 2001; Chung et al., 2015) .

Another advantage of electrical discharge technology is its adaptability to different types of contaminated water. This technology can be used for treating industrial effluents, household waste, and agricultural wastewater. Research has shown that this method can effectively eliminate even hard-to-decompose organic pollutants, heavy metals, and petroleum products (Boyko and Makogon, 2020).

The wastewater treatment method using electrical discharge meets modern environmental standards. It supports principles of sustainable development and efficient resource utilization. By ensuring water

Quick Response Code	Access this article online	
	Website: www.watconman.org	**DOI:** 10.26480/wcm.02.2025.40.48

Cite The Article: Askar Abdykadyrov, Maxat Mamadiyarov, Kyrmyzy Taissariyeva, Sunggat Marxuly, Nuridin Junussov, Muratbek Yermekbayev, Abdurazak Kasimov, Anar Khabay (2025). Study of the Wastewater Treatment Process Using Electrical Discharge. *Water Conservation & Management, 9(1): 40-48.*

cleanliness, it facilitates the restoration and preservation of natural ecosystems (Macedonio et al., 2012; Alkhadra et al., 2022). Currently, this technology plays an important role in protecting water resources and enhancing ecological safety.

For this scientific research, we developed a pilot ETRO-02 ozonator unit based on electrical discharge specifically for wastewater treatment near Talgar city in the Almaty region. This is necessary because the community within a 150-meter radius of the wastewater source is facing environmental issues. The residents of the village urgently need access to quality water and clean air. To address this environmental issue, we have decided to carry out wastewater treatment efforts at the Kazakh National Research Technical University named after K.I. Satbayev.

2. METHODS AND METHODOLOGY

The treatment of wastewater and the surrounding air through the effect of electrical discharge is one of the important research areas of modern times. Wastewater collected from various cities is rich in pollutants, and its effective purification plays a crucial role in solving environmental problems. In this study, we examined the possibility of decomposing harmful substances in wastewater using an electrical discharge. Unlike conventional purification methods, electrical discharge promotes the formation of ozone, hydroxyl radicals, and other active substances in wastewater. These compounds effectively decompose organic and inorganic pollutants, thereby purifying the water (Jałowiecki,et al., 2024).

To conduct the study, wastewater samples were taken and initially passed through a mechanical filter. This procedure helped to remove large particles and debris, leaving clean samples for subsequent processes. Then, the water was treated with high-voltage electrical discharge. High-frequency discharge generates a significant amount of ozone, which has a substantial impact on organic pollutants. Low-frequency discharges consistently produce hydroxyl radicals, which demonstrated high efficiency in reducing chemical contamination. Now, let us proceed with theoretical analysis. To perform theoretical calculations, we will apply reaction equations and transformations corresponding to each stage of the process. The model includes mechanical filtration, high-frequency electrical discharge for ozone generation, and low-frequency discharge for hydroxyl radical production (Abdykadyrov et al., 2023).

Mechanical filtration of large particles and impurities. During the mechanical filtration stage, the concentration of large particles in wastewater is reduced.

$$C_{filtered} = C_{initial} \cdot (1 - \eta_{filter}) \quad (1)$$

where: $C_{initial}$ is the initial concentration of large particles (mg/L or another appropriate unit), η_{filter} is the efficiency of the mechanical filter. *Example:* If the initial concentration $C_{initial}$ = 100mg/L and the filter η_{filter} = 0.9 (90%), then: $C_{filtered} = 100 \cdot (1 - 0{,}9) = 10\,\frac{mg}{L}$. The concentration of large particles after filtration is 10 mg/L.

Ozone Generation by High-Voltage Electric Discharge. Ozone generation can proceed according to the following reaction:

$$O_2 + e^- \rightarrow O + O \quad (2)$$

$$O_2 + O \rightarrow O_3 \quad (3)$$

During high-frequency discharge, ozone concentration can be expressed as a function of time:

$$\frac{d[O_3]}{dt} = k_{ozone} \cdot [O_2] \cdot I_{high} - k_{decomp} \cdot [O_3] \quad (4)$$

where: k_{ozone} is the rate constant of ozone formation, [O2] is the concentration of dissolved oxygen (mol/L), I_{high} is the intensity of the high-frequency discharge, k_{decomp} is the rate constant of ozone decomposition. Example: If the initial oxygen concentration $[O_2]$ = 0.02 mol/L, I_{high} = 1.5, k_{ozone} = 0.1 and k_{decomp} = 0.05 then the rate of change of ozone concentration over time is: $\frac{d[O_3]}{dt} = 0{,}1 \cdot 0{,}02 \cdot 1{,}5 - 0{,}05 \cdot [O_3]$, $\frac{d[O_3]}{dt} = 0{,}003 - 0{,}05 \cdot [O_3]$. This equation can be solved numerically to determine the time-dependent concentration of ozone.

Hydroxyl Radical Generation by Low-Frequency Electric Discharge. When water is treated with low-frequency discharge, the concentration of hydroxyl radicals ($\boldsymbol{OH^*}$) increases, which is crucial for breaking down organic pollutants:

$$\frac{d[OH^*]}{dt} = k_{OH} \cdot [H_2O] \cdot I_{low} - k_{react} \cdot [OH^*] \cdot [C_{organic}] \quad (5)$$

where: k_{OH} is the rate constant of hydroxyl radical formation, $[H_2O]$ is the concentration of water molecules, I_{low} is the intensity of the low-frequency discharge, k_{react} is the rate constant of the reaction between hydroxyl radicals and organic substances. Example: If k_{OH} = 0.05, $[H_2O]$ = 55.5 mol/L, I_{low} = 0.8, k_{react} = 0.03, and the concentration of organic pollutants $[C_{organic}]$ = 0.01, then: $\frac{d[OH^*]}{dt} = 0{,}05 \cdot 55{,}5 \cdot 0{,}8 - 0{,}03 \cdot [OH^*] \cdot 0{,}01$, $\frac{d[OH^*]}{dt} = 2{,}22 - 0{,}0003 \cdot [OH^*]$. This equation can be solved to find the concentration of hydroxyl radicals.

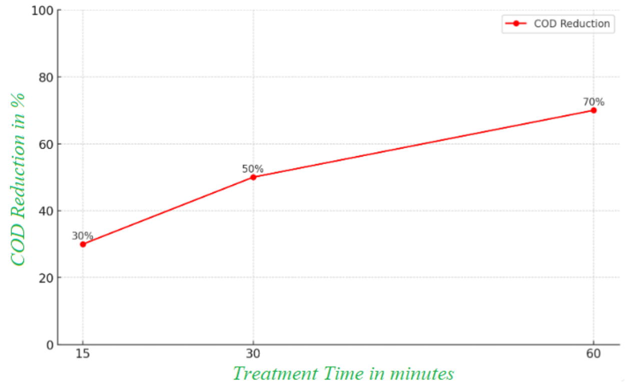
Reduction of Organic Pollutants Concentration. The concentration of organic pollutants decreases due to the effects of ozone and hydroxyl radicals. This process can be represented by the following equation:

$$\frac{d[C_{organic}]}{dt} = - k_{react} \cdot [OH^*] \cdot [C_{organic}] - k_{ozone.react} \cdot [O_3] \cdot [C_{organic}] \quad (6)$$

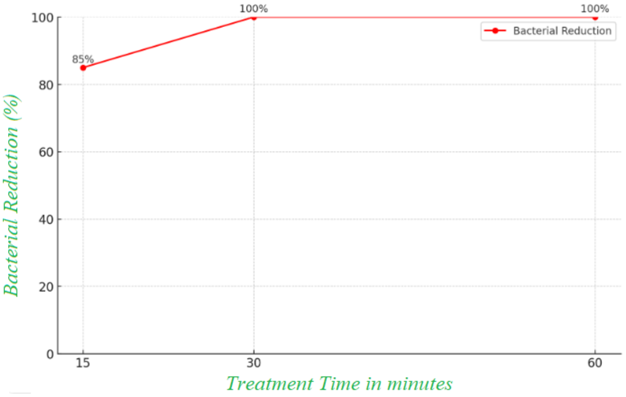
where: k_{ozone_reactk} is the rate constant of the reaction between ozone and organic pollutants.

These theoretical calculations allow us to model ozone and hydroxyl radical formation and the reduction of organic contaminants during various stages of wastewater treatment by electric discharge.

During the procedure, various voltage levels and treatment durations were applied. For example, a voltage of 15 kV was tested over 15, 30, and 60 minutes. Digital data was collected during the experiments, allowing for a comparison of the initial and final composition of the water. When high-frequency discharge was applied, the chemical oxygen demand (COD) of the water decreased by up to 70% within 60 minutes. In biological studies, the bacterial count dropped by 85% within the first 30 minutes and was completely eliminated by 60 minutes. The research results were analyzed and graphically represented using Python. The outcome can be seen in Figure 1 below [18,19].



a) COD Reduction Over Time in Wastewater Treatment by Electrical Discharge



b) Bacterial Count Reduction Over Time in Wastewater Treatment by Electrical Discharge

Figure 1: Effectiveness of Wastewater Treatment by Electrical Discharge

In Figure 1a, the reduction in Chemical Oxygen Demand (COD) levels in wastewater is shown in relation to the treatment time with electrical discharge. After 15 minutes of treatment, COD decreased by 30%, by 50% at 30 minutes, and by 70% at 60 minutes. These results indicate that as the treatment time increases, the reduction in COD levels significantly improves. In Figure 1b, the level of bacterial elimination is shown in relation to treatment time with electrical discharge. After 15 minutes, bacterial count decreased by 85%, reaching 100% elimination after 30 minutes, meaning complete eradication. After 30 minutes, no bacteria remained, and the elimination level remained consistently at 100% up to 60 minutes.

The effect of electrical discharge was evaluated not only by its efficiency but also by its power consumption. When treating one liter of wastewater with a discharge of 15 kV, the power consumption was 0.5 kWh. This method is environmentally effective, as electric power helps to eliminate pollutants to obtain clean water. Such technologies may find broad applications in waste processing in the future. The high efficiency of the method was demonstrated in laboratory results, indicating the need for further development. The use of such technologies in urban sewer systems can help conserve clean water and maintain ecological balance. The research results can be observed in Figure 2 below.

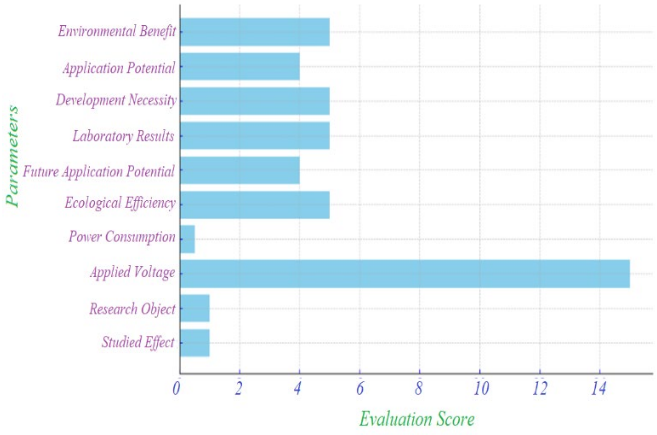
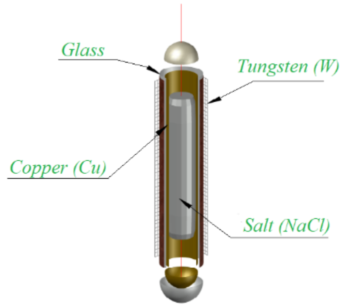


Figure 2: Evaluation of Research Outcomes

In Figure 2, the Applied Voltage parameter is shown to be 15 kV, while Power Consumption is at the level of 0.5 kWh, indicating the energy efficiency of this method. The Ecological Efficiency, Laboratory Results, and Environmental Benefit parameters were rated with a maximum score of 5, highlighting the ecological and scientific value of the method. Future Application Potential and Application Potential were rated at 4, indicating a high potential for future use of the method.

3. RESULTS AND DISCUSSIONS

Based on theoretical studies in the Materials and Methods section, a laboratory model of the pilot ETRO-02 ozonator unit, based on electrical discharge, was developed at the Department of Electronics, Telecommunications, and Space Technologies of the Kazakh National Research Technical University named after K.I. Satbayev. The structural design and overall appearance of the laboratory model are shown in Figure 3 below.



a) Structure of the Ozonator

в) Laboratory Model for Conducting Experimental Work

Figure 3: General View of the Laboratory Setup Based on Water Ozonation

And the overall technological system of the setup is presented in Figure 4 below.

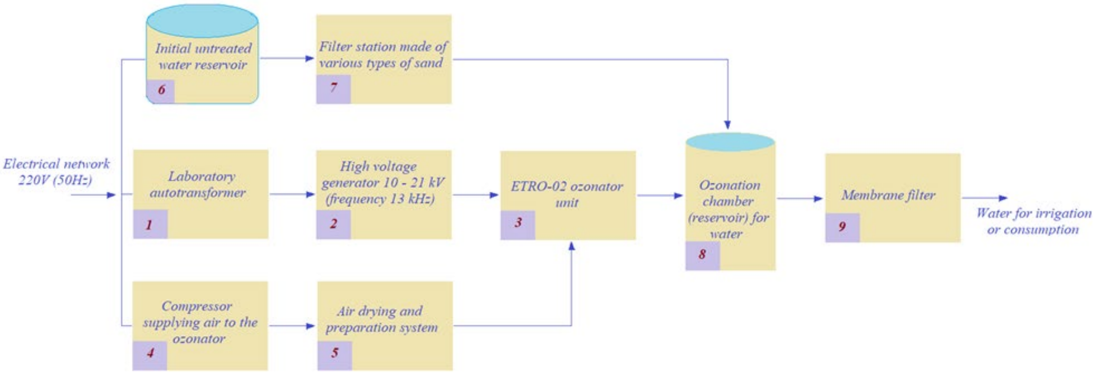


Figure 4: Ozonation-based water filtration process

This Figure 4 describes the full structure of the water purification system based on the ozonation process. The operation of the system consists of several stages, and each component has a specific function. Below is an analysis of each component and its role in the system:

- *Laboratory autotransformer* – this component regulates and provides the necessary electrical power to the entire system. It takes power from an external 220V (50Hz) electrical network and adjusts it to the required level for the ozonator and other components. The autotransformer ensures the stable and reliable operation of the system;
- *High voltage generator 10-21 kV* – a generator that supplies high voltage with a frequency of 13 kHz. This generator ensures the normal operation of the ozonator since high voltage and a stable frequency are required for ozone-generating reactions. It transforms oxygen molecules in the system into ozone molecules;
- *ETRO-02 ozonator unit* – the ozonator unit is the central element of the system. It generates ozone from air and purifies the water through an oxidation process. The use of ozone is an effective technology for disinfection and the removal of harmful contaminants;
- *Compressor supplying air to the ozonator and Air drying and preparation system* – these two components support the operation of the ozonator. The compressor supplies the necessary airflow to the ozonator, and the air drying and preparation system reduces the humidity in the air, which is essential for efficient ozone production;
- *Initial untreated water reservoir* – the untreated water that needs to be purified is collected in this reservoir. This water then passes through the next stages of the system, including ozonation and filtration processes;
- *Filter station made of various types of sand* – the filtration of large particles from the water is carried out at this stage. The sand filter mechanically cleans the water, removing large impurities, which enhances the overall efficiency of the process;

- *Ozonation chamber* – water is treated with ozone in this chamber, where it undergoes an oxidation reaction with harmful contaminants. During this stage, the water is chemically disinfected;

- *Membrane filter* – after the ozonation process, the water passes through a membrane filter, which removes microparticles and residual contaminants. This filter represents the final stage of purification, allowing for the production of clean water;

- *Water for irrigation or consumption* – finally, the purified water is ready for use, either for consumption or irrigation. As the water has passed through the ozonation and filtration processes, it is of high quality and completely free from harmful substances.

This system illustrates a laboratory setup designed for effective water purification. It can be used for conducting experiments and modifying the chemical and physical properties of water. The ozonation process is the core part of the system, and its main objective is to remove harmful contaminants in the water through oxidation.

3.1 Experimental Results

To conduct the scientific research experiment, water was collected from a specific site (Figure 5) and delivered to a scientific laboratory. The initial concentration of toxic chemical compounds in the water can be observed in Table 1.

Figure 5: The research object is located in Talgar village, Almaty region. Wastewater discharged from sewage

Table 1: Initial Concentration and Maximum Allowable Limits of Harmful Substances in Water and Their Impact on Human Health

Chemical Component	Initial Concentration of Harmful Substances in Water (mg/L)	MAC (mg/L)	Harmful Effects on Human Health	Explanation
Ammonia (NH_3)	10 - 30	2,0	Harmful to the respiratory system, risk of poisoning	Nitrogen compound, decomposition of organic matter
Nitrates (NO_3^-)	5 - 50	45,0	Can cause methemoglobinemia	Oxidation product of organic matter
Nitrites (NO_2^-)	0,01 – 0,5	3,3	Disrupts oxygen transport, can lead to poisoning	Intermediate product of oxidation process
Phosphates (PO_4^{3-})	5 - 30	0,5	May affect mineral metabolism in the body	Phosphorus compounds, mainly from household chemicals
Chlorides (Cl^-)	50 - 250	350,0	Puts strain on kidneys, affects digestive system	From table salt and household chemicals
Sulfates (SO_4^{2-})	20 - 200	500,0	Can cause irritation of the digestive tract	Sulfur compounds from industrial waste
Iron (Fe)	0,1 - 2,0	0,3	Excess iron affects the body's oxidation processes	Result of redox reactions
Copper (Cu)	0,05 – 1,0	1,0	Excess metal is harmful to the nervous system	From industrial wastewater
Zinc (Zn)	0,1 – 2,0	5,0	Irritation of the digestive tract, risk of poisoning	From industrial wastewater
Lead (Pb)	0,001 – 0,1	0,03	Causes severe harm to the nervous system, high risk of poisoning	Industrial pollution, old pipes
Chemical Oxygen Demand (COD)	200 - 800	Not regulated	No specific data	Oxygen required for the oxidation of organic matter
Biochemical Oxygen Demand (BOD)	100 - 400	Not regulated	No specific data	Breakdown of organic matter by microorganisms
Calcium (Ca)	50 - 200	Not regulated	Excess can lead to kidney stones	From natural sediments and industrial discharges
Magnesium (Mg)	10 - 100	Not regulated	No specific data	From natural sediments and industrial waste

The table shows the initial concentration of harmful substances in wastewater and their maximum allowable limits. When the concentration of each chemical element exceeds the permissible limit, it can have harmful effects on human health, for example, posing risks to the respiratory or nervous system.

To solve this problem, the process of oxidizing and purifying harmful

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compounds in water after filtration was carried out in two approaches. The first approach involved keeping the ozone concentration constant (ozone concentration C, 600 g/hour) and varying the oxidation time. The results of this study are presented in Table 2 below. In contrast, the second approach kept the oxidation time constant while varying the ozone concentration. The results of this study are presented in Table 3 below.

1. Research Results for the First Approach:

Table 2: Research Results for the First Approach

Chemical Component	Initial Concentration of Harmful Substances in Water (mg/L)	MAC (mg/L)	The duration of water treatment with ozone (ozone concentration C, 600 g/hour)			
			t_1 = 10 minutes	t_2 = 20 minutes	t_3 = 30 minutes	t_4 = 40 minutes
Ammonia (NH_3)	130	2,0	95	48	17	1
Nitrates (NO_3^-)	50	45,0	35	28	12	7
Nitrites (NO_2^-)	0,5	3,3	0,3	0,1	0,02	0
Phosphates (PO_4^{3-})	30	0,5	18	6	2	0
Chlorides (Cl^-)	250	350,0	178	103	45	20
Sulfates (SO_4^{2-})	200	500,0	156	112	78	18
Iron (Fe)	2,0	0,3	1,3	0,98	0,56	0,28
Copper (Cu)	1,0	1,0	0,95	0,68	0,54	0,35
Zinc (Zn)	2,0	5,0	1,58	1,25	0,85	0,45
Lead (Pb)	0,1	0,03	0	0	0	0
Chemical Oxygen Demand (COD)	800	Not regulated	687	458	256	0
Biochemical Oxygen Demand (BOD)	400	Not regulated	235	156	98	0
Calcium (Ca)	200	Not regulated	145	85	47	0
Magnesium (Mg)	100	Not regulated	58	28	3	0

This table shows the results of water treatment with ozone over different time intervals (10, 20, 30, and 40 minutes). The concentration of ammonia (NH_3) significantly decreased from an initial concentration of 130 mg/L to 1 mg/L after 40 minutes of treatment. Nitrates (NO_3^-) reduced from 50 mg/L to 7 mg/L, and nitrites (NO_2^-) completely disappeared after 30 minutes. Phosphates (PO_4^{3-}) dropped from 30 mg/L to 0 mg/L after 40 minutes, demonstrating the effectiveness of the process for phosphorus compounds. Other harmful components such as sulfates (SO_4^{2-}), iron (Fe), and copper (Cu) also showed significant reductions over time, indicating the efficiency of ozone treatment in reducing contamination.

Now let's visualize the data from this table in graphical form. The research results are presented in Figures 6, 7, and 8 below.

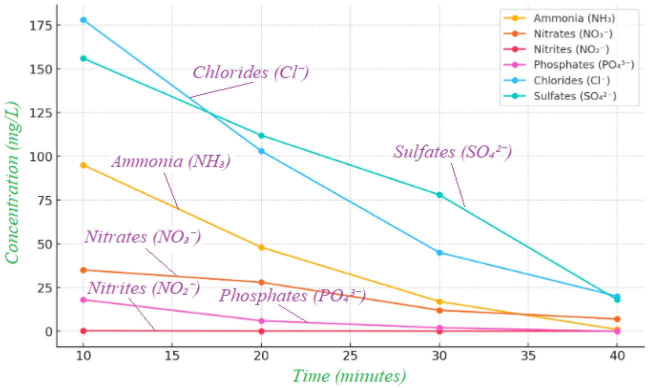

Figure 6: Change in Concentration of Ammonia, Nitrates, Nitrites, Phosphates, Chlorides, and Sulfates during Water Purification with Ozone

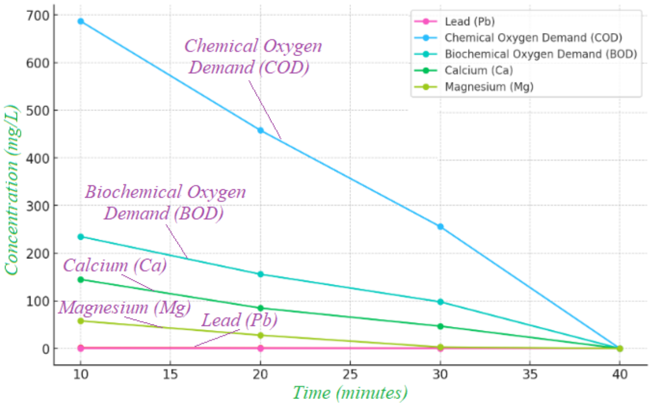

Figure 7: Change in Concentration of Lead, COD, BOD, Calcium, and Magnesium during Water Purification with Ozone

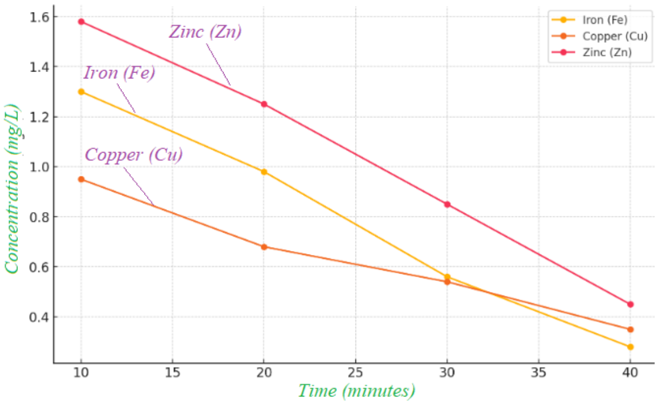

Figure 8: Change in Concentration of Iron, Copper, and Zinc during Water Purification with Ozone

These Figures 6, 7, and 8 show the reduction in concentrations of various chemical compounds over time during water purification with ozone. In the first graph, significant decreases in the concentrations of ammonia, nitrates, nitrites, phosphates, chlorides, and sulfates are observed. The second graph also demonstrates reductions in lead, COD, BOD, calcium, and magnesium concentrations over time. The third graph shows a steady decline in the concentrations of iron, copper, and zinc, indicating the effectiveness of the water purification process using ozone.

2. Research Results for the Second Approach:

Table 3: Research Results for the Second Approach

Chemical Component	Initial Concentration of Harmful Substances in Water (mg/L)	MAC (mg/L)	The process of water purification with ozone (oxidation time 40 minutes)			
			C_1 = 150 g/hour	C_2 = 300 g/hour	C_3 = 450 g/hour	C_4 = 600 g/hour
Ammonia (NH_3)	130	2,0	87	45	14	1
Nitrates (NO_3^-)	50	45,0	33	25	9	7
Nitrites (NO_2^-)	0,5	3,3	0,3	0,1	0,02	0
Phosphates (PO_4^{3-})	30	0,5	19	8	4	0
Chlorides (Cl^-)	250	350,0	167	98	42	20
Sulfates (SO_4^{2-})	200	500,0	162	117	85	18
Iron (Fe)	2,0	0,3	1,28	0,88	0,65	0,28
Copper (Cu)	1,0	1,0	0,87	0,59	0,48	0,35
Zinc (Zn)	2,0	5,0	1,48	1,18	0,78	0,45
Lead (Pb)	0,1	0,03	0	0	0	0
Chemical Oxygen Demand (COD)	800	Not regulated	598	398	263	0
Biochemical Oxygen Demand (BOD)	400	Not regulated	248	168	78	0
Calcium (Ca)	200	Not regulated	138	78	45	0
Magnesium (Mg)	100	Not regulated	59	33	5	0

This table shows the effect of different ozone concentrations (150 g/hour, 300 g/hour, 450 g/hour, 600 g/hour) during the water purification process. The initial concentration of ammonia (NH_3) was 130 mg/L, which decreased to 1 mg/L after 40 minutes of treatment with 600 g/hour ozone. Nitrates (NO_3^-) dropped from an initial 50 mg/L to 7 mg/L at the highest ozone concentration. Phosphates (PO_4^{3-}) were completely removed, decreasing from 30 mg/L to 0 mg/L at 600 g/hour. Additionally, chlorides (Cl^-) and sulfates (SO_4^{2-}) also significantly decreased, with the purification efficiency increasing as the ozone concentration increased.

Now let's visualize the data from this table in graphical form. The research results are presented in Figures 9, 10 and 11 below.

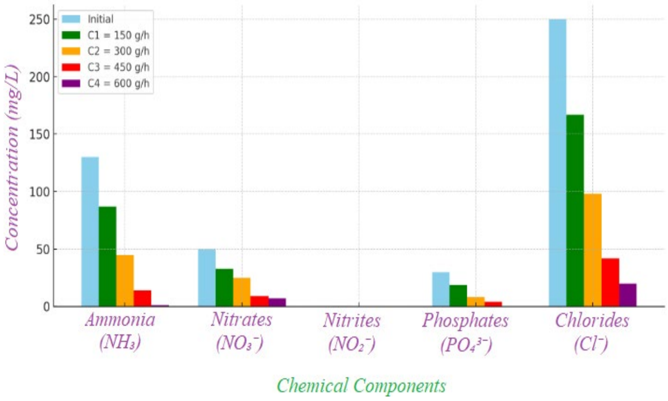

Figure 9: Water Purification: Ammonia, Nitrates, Nitrites, Phosphates, Chlorides

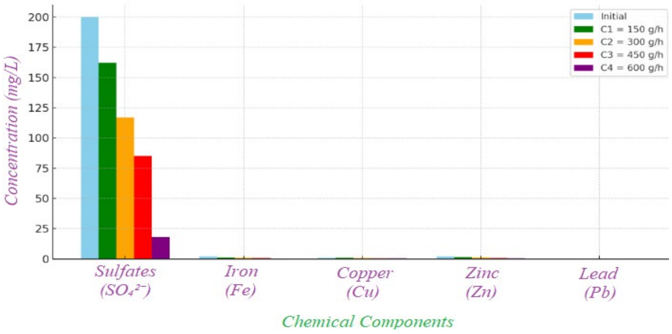

Figure 10. Water Purification: Sulfates, Iron, Copper, Zinc, Lead

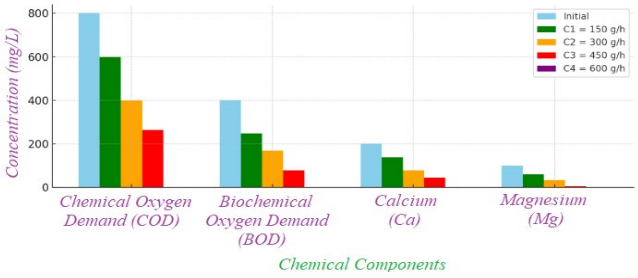

Figure 11. Water Purification: Chemical Oxygen Demand, Biochemical Oxygen Demand, Calcium, Magnesium

These three graphs (Figure 9,10 and 11) demonstrate the effectiveness of the water purification process using different amounts of ozone (150 g/h - 600 g/h). The concentrations of pollutants like ammonia, nitrates, phosphates, chlorides, iron, and lead significantly decrease as the amount of ozone increases. Notably, at the highest concentration (600 g/h), many harmful substances drop below the MAC limit or are completely eliminated. Overall, the effectiveness of ozone treatment depends on the initial concentration of pollutants and the amount of ozone used.

3.2 The Mathematical Model of Ozone's Chemical Interaction with Harmful Substances In Water

Ozone (O_3) is a highly effective oxidizer that reacts with harmful substances in water, breaking them down or converting them into harmless products. The mathematical model of ozone's effectiveness in reducing the concentration of various pollutants can be developed using chemical reaction equations and kinetics. Below is the mathematical model with chemical reaction equations for each substance.

Ammonia (NH_3) Model. Ammonia reacts with ozone and is oxidized into nitrogen and water:

$$4NH_3 + 3O_3 \rightarrow 2N_2 + 3H_2O + 3O_2 \qquad (7)$$

Mathematically, this reaction can be described by a first-order kinetic equation:

$$\frac{d[NH_3]}{dt} = -k_1[NH_3][O_3] \qquad (8)$$

where: $[NH_3]$ is the concentration of ammonia, $[O_3]$ is the concentration of ozone, k_1 is the rate constant of the reaction.

Nitrites (NO_2^-) and Nitrates (NO_3^-) Model. Nitrites are oxidized by ozone to form nitrates:

$$2NO_2^- + O_3 \rightarrow 2NO_3^- \qquad (9)$$

The kinetic equation for nitrites is:

$$\frac{d[NO_2^-]}{dt} = -k_2[NO_2^-][O_3] \qquad (10)$$

For nitrates:

$$\frac{d[NO_3^-]}{dt} = k_2[NO_2^-][O_3] \qquad (11)$$

Phosphates (PO_4^{3-}) Model. Phosphates do not directly react with ozone, but they can be associated with organic compounds that break down during the process:

$$\frac{d[\mathrm{PO_4}^{3-}]}{dt} = -k_3[\mathrm{PO_4}^{3-}][O_3] \qquad (12)$$

where k_3 is the rate constant for phosphates.

Chlorides (Cl^-) Model. Chlorides may not directly react with ozone, but organic chlorides may be broken down by ozone:

$$\frac{d[Cl^-]}{dt} = -k_4[Cl^-][O_3] \qquad (13)$$

Iron (Fe), Copper (Cu), and Zinc (Zn) Model. These metals are oxidized by ozone into insoluble oxides. For example, iron oxidation can be represented as:

$$2Fe^{2+} + O_3 + 2H_2O \rightarrow 2FeO(OH) + O_2 + 4H^+ \qquad (14)$$

The kinetic equation for iron is:

$$\frac{d[Fe^{2+}]}{dt} = -k_5[Fe^{2+}][O_3] \qquad (15)$$

Lead (Pb) Model. Lead does not directly react with ozone but may be removed due to other chemical processes:

$$\frac{d[Pb]}{dt} = -k_6[Pb][O_3] \qquad (16)$$

Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) Models. COD and BOD represent the organic load in the water. Ozone oxidizes organic matter, breaking it down into carbon dioxide and water:

$$\text{Organic Matter} + O_3 \rightarrow CO_2 + H_2\mathrm{O} \qquad (17)$$

The kinetic equation for COD is:

$$\frac{d[\mathrm{COD}]}{dt} = -k_7[COD][O_3] \qquad (18)$$

And for BOD:

$$\frac{d[\mathrm{BOD}]}{dt} = -k_8[BOD][O_3] \qquad (19)$$

General Mathematical Model. The overall system of equations describing the concentration changes of each pollutant over time is:

$$\frac{d[NH_3]}{dt} = -k_1[NH_3][O_3] \qquad (20)$$

$$\frac{d[NO_2^-]}{dt} = -k_2[NO_2^-][O_3] \qquad (21)$$

$$\frac{d[NO_3^-]}{dt} = k_2[NO_2^-][O_3] \qquad (22)$$

$$\frac{d[\mathrm{PO_4}^{3-}]}{dt} = -k_3[\mathrm{PO_4}^{3-}][O_3] \qquad (23)$$

$$\frac{d[Cl^-]}{dt} = -k_4[Cl^-][O_3] \qquad (24)$$

$$\frac{d[Fe^{2+}]}{dt} = -k_5[Fe^{2+}][O_3] \qquad (25)$$

$$\frac{d[\mathrm{COD}]}{dt} = -k_7[COD][O_3] \qquad (26)$$

$$\frac{d[\mathrm{BOD}]}{dt} = -k_8[BOD][O_3] \qquad (27)$$

Constant Ozone Concentration. If we assume a constant ozone concentration ($[O_3]$ = const), each equation simplifies into a first-order differential equation where the concentration of pollutants decreases exponentially:

$$[NH_3](t) = [NH_3]_0 \cdot e^{-k_1[O_3]t} \qquad (28)$$

where $[NH_3]_0$ is the initial concentration of ammonia. Similarly, the concentrations of other pollutants will follow an exponential decay model over time.

This mathematical model describes the reduction of harmful substances in water depending on the amount of ozone used and the time of treatment. Each pollutant's concentration can be calculated based on the rate constants and the ozone concentration, helping optimize the water purification process and determine the necessary ozone dosage.

3.3 Analysis of Research Results

In this process, strong oxidizers such as ozone and hydroxyl radicals are formed. The study demonstrated that high - and low-frequency discharges effectively decompose organic and inorganic pollutants and eliminate bacteria. The method has environmental and economic advantages, as it provides water purification without chemical additives and with low energy consumption. The analysis of the research results is as follows:

- The wastewater treatment process using ozone showed a significant reduction in harmful substances over time and with increasing ozone concentration;
- As seen in Figure 6, pollutants like ammonia (NH_3), nitrates (NO_3^-), nitrites (NO_2^-), phosphates (PO_4^{3-}), chlorides (Cl^-), and sulfates (SO_4^{2-}) decreased substantially during the treatment, with some pollutants being fully eliminated after 40 minutes of treatment;
- Phosphates were reduced to zero, demonstrating the effectiveness of ozone treatment in breaking down phosphorus compounds;
- Figure 7 demonstrates the reduction in concentrations of lead (Pb), COD, BOD, calcium (Ca), and magnesium (Mg) over time. Lead was completely eliminated during the treatment, while COD and BOD showed substantial reductions, indicating improved water quality;
- The highest ozone concentration (600 g/h) achieved almost complete elimination of ammonia and other pollutants, indicating that ozone dosage plays a crucial role in the efficiency of water treatment;
- The oxidation time also has a significant impact on the reduction rates, with longer treatment times resulting in higher reductions of contaminants;
- Figure 8 illustrates a steady decline in the concentrations of metals like iron (Fe), copper (Cu), and zinc (Zn) during water purification. This indicates that ozone is effective at removing heavy metals;

Cite The Article: Askar Abdykadyrov, Maxat Mamadiyarov, Kyrmyzy Taissariyeva, Sunggat Marxuly, Nuridin Junussov, Muratbek Yermekbayev, Abdurazak Kasimov, Anar Khabay (2025). Study of the Wastewater Treatment Process Using Electrical Discharge. *Water Conservation & Management, 9(1): 40-48.*

- The bacterial count dropped by 85% after the first 30 minutes of treatment, reaching 100% elimination by 60 minutes, showing ozone's ability to disinfect water effectively;
- The electrical discharge method demonstrated a power consumption of 0.5 kWh per liter, making it a cost-efficient and environmentally friendly solution;
- The research results suggest that the ozone treatment method could be applied at a larger scale for wastewater treatment in urban areas to improve water quality and protect ecosystems.

These results, depicted in the graphs, demonstrate the clear effectiveness of ozone in reducing both chemical and biological contaminants in wastewater.

4. CONCLUSION

This research demonstrated the effectiveness and environmental safety of wastewater treatment using electrical discharge. The use of high- and low-frequency electrical discharges to reduce chemical and biological pollutants in wastewater has proven to be an effective method. The study recorded quantitative changes in the chemical and biological composition of water, evaluating the effects of different ozone concentrations and treatment durations. For instance, with an ozone concentration of 600 g/h, the initial concentration of ammonia decreased from 130 mg/L to 1 mg/L, almost completely eliminating ammonia. Additionally, nitrites were completely removed, and phosphates were fully broken down after 40 minutes of treatment.

Another key finding was the significant reduction in chemical oxygen demand (COD). Over 60 minutes, COD decreased by up to 70%, indicating efficient removal of organic pollutants from the water. Similarly, biochemical oxygen demand (BOD) levels also declined, reflecting the breakdown of organic matter caused by microorganisms. These data confirm the high efficiency of electrical discharge in decomposing organic substances.

The study also demonstrated a significant reduction in bacterial count. After the first 30 minutes, bacteria levels dropped by 85%, and after 60 minutes, they were completely eliminated. This indicates that ozone and hydroxyl radicals formed during electrical discharge play a critical role in disinfecting the water. Ozone production during the electrical discharge is the primary mechanism for bacteria elimination, making this method highly effective in sterilizing wastewater.

In terms of energy consumption, the method also proved to be efficient. For example, treating 1 liter of wastewater at 15 kV voltage consumed only 0.5 kWh of energy. This highlights the process as a low-energy, environmentally friendly technology for water purification. Furthermore, the method requires no chemical additives, demonstrating its ability to effectively remove pollutants without harming the environment.

Another advantage of this method is its versatility and flexibility. Wastewater treatment using electrical discharge can be applied to various types of wastewater, including industrial, household, and agricultural wastewater, indicating its wide application potential. The results showed that this method is effective even for the removal of hard-to-decompose pollutants, such as heavy metals, petroleum products, and organic substances.

The use of this method in wastewater treatment aligns with modern environmental standards. Currently, the technology is being used in many countries and plays a key role in enhancing environmental safety and protecting water resources. The method is also economically advantageous since it requires only electrical energy and no additional chemicals, making it cost-effective and environmentally sustainable. The method supports principles of sustainable development and efficient resource use.

This research confirms that the technology of generating ozone and hydroxyl radicals through electrical discharge is a modern and effective approach to wastewater treatment. The method efficiently removes heavy metals, organic pollutants, and bacteria, while consuming low amounts of energy and maintaining an environmentally friendly process. Furthermore, the potential for industrial-scale application of this method is being explored, as it could become a foundation for large-scale wastewater treatment in the future.

The results of this study indicate that the method has promising potential and could be widely used in future water purification processes. The technology of water purification through electrical discharge significantly contributes to ensuring environmental cleanliness, protecting human health, and preserving natural water resources.

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