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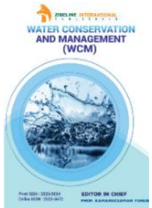

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RESEARCH ARTICLE

STUDY OF THE DISINFECTION PROCESS OF HARMFUL MICROORGANISMS FOUND IN THE VYACHESLAV RESERVOIR USING A PILOT INSTALLATION BASED ON OZONE TECHNOLOGY

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ABSTRACT

This scientific research focuses on the study of the disinfection process of harmful microorganisms found in the Vyacheslav Reservoir using the ETRO - 02 ozonator installation based on pilot electrical corona discharge and ozone technology. The objective of the research is to determine the effectiveness of ozone technology in eliminating microorganisms in water and compare it with other disinfection methods. The materials and methods section reveals that ozone eliminates total coliform bacteria within 2 - 4 minutes at a rate of 99 - 100%, which is significantly faster than chloramine (which takes 15 - 30 minutes). Additionally, it was found that ozone decomposes into oxygen after use, leaving no harmful residues. The research results showed that ozone eliminates Clostridium spores by 85 - 90% within 10 - 15 minutes, while chloramine requires more time to reach the same efficiency. Ozone technology demonstrated an effectiveness of 95 - 99% at a pH range of 4.0 - 5.0, proving its suitability for different water conditions. Moreover, ozone works effectively under high temperatures and pressure. The findings indicated that at an ozone concentration of 1.0 mg/L, all harmful microorganisms in water are completely eliminated within 20 minutes. The research was conducted both theoretically and experimentally, with the mathematical model of water disinfection coded in Python. Mathematical calculations were performed using the SMath Solver software. In conclusion, ozone technology has been proven to be an effective, safe, and environmentally friendly method for water purification.

The primary objective of this study is to evaluate the effectiveness of ozone technology for water disinfection and to compare its efficiency with other disinfection methods.

KEYWORDS

Ozone technology, reservoir, harmful microorganisms, pilot installation, disinfection process, water purification, ecological monitoring.

1. INTRODUCTION

This study aims to explore the efficiency of ozone technology in water disinfection, emphasizing its advantages over conventional methods and its potential for broader environmental applications. This research investigates innovative water treatment technologies to address challenges faced in densely populated regions, emphasizing the ecological and health benefits of ozone technology.

Ensuring the quality of reservoirs and protecting them from harmful microorganisms is one of the important tasks for meeting modern environmental requirements and safeguarding public health. This issue is particularly significant in densely populated areas, where human activities and natural factors contribute to an increase in pollutants and microorganisms entering the reservoirs (Gomes et al., 2019; Xu et al., 2023). It is proposed to use pilot installations based on ozone technology for the effective disinfection of microorganisms found in the Vyacheslav reservoir (Wang et al., 2022; Marszałek et al., 2024). Ozone technology is widely used for water disinfection due to its high efficiency in destroying microorganisms and harmful organic substances dissolved in water (Abdykadyrov et al., 2024).

Ozone's strong oxidizing properties make it an effective tool for eliminating microorganisms such as bacteria, viruses, and fungi. Ozone molecules disrupt the cellular membranes of microorganisms, halting their survival. Furthermore, one of the advantages of ozone is that it does not produce harmful by-products after use, making it an environmentally friendly solution compared to chlorine or other chemical disinfection methods (Epelle et al., 2022; Xue et al., 2023; Westover et al., 2022; Kovač et al., 2023).

The primary goal of the pilot ozonator installation is to disinfect harmful

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microorganisms in the Vyacheslav reservoir and improve water quality. The solubility of ozone in water and its disinfecting properties allow for high-quality water purification. Additionally, ozone technology operates effectively under high pressure and temperature conditions, increasing the process's productivity. The use of ozone in the reservoir quickly eliminates bacteria and viruses in the water, demonstrating the short reaction time (Azuma et al., 2023; Abdykadyrov et al., 2023).

In the pilot installation, the dispersion of ozone and its effect level are studied, with various parameters such as temperature and pressure being monitored to ensure an efficient disinfection process. This system is a critical step toward ensuring water's ecological safety and public health by eliminating harmful microorganisms. Research results show that ozone technology provides a high level of destruction for E. coli, enterococci, and other dangerous microorganisms in the Vyacheslav reservoir (Wani et al., 2015; Mukherjee et al., 2023; Abdykadyrov, 2024).

This technology can be effectively applied not only to reservoirs but also to urban water systems. The economic efficiency and compliance of ozone technology with high environmental standards make it a promising method for water resource protection. Currently, ozone installations are among the most advanced technologies for water purification, as they ensure the complete destruction of organic substances without leaving harmful residues in the water (Aivazidou et al., 2021; Remondino and Valdenassi, 2018; Arden et al., 2020).

In the city, drinking water has been noted to have an odor of algae. This odor is mainly caused by the chemical compounds Geosmin and 2-Methylisoborneol (MIB). These compounds are produced by algae and cyanobacteria (blue-green algae) in the water. Geosmin and MIB are organic compounds released during the decomposition of soil or plant material in the water. Even in very low concentrations, they produce strong odors, which affect water quality. Geosmin creates a scent similar to that of soil or earth, while MIB often gives a moldy smell. Although these odors do not pose a health risk, they can negatively impact the organoleptic quality of the water (Aivazidou, E., Banias, G., Lampridi, M., Vasileiadis, G., Anagnostis, A., Papageorgiou, E., and Bochtis, D., 2021; Remondino and Valdenassi, 2018).

Currently, there are several methods available for disinfecting and purifying water from harmful microorganisms. The advantages and disadvantages of these methods can be observed in Figure 1 below.

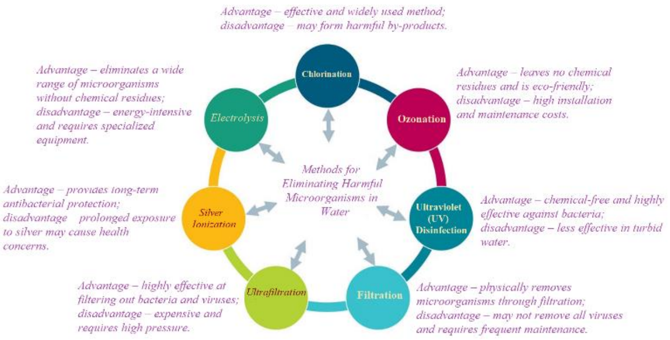


Figure 1: Water Treatment Methods: Advantages and Disadvantages of Microorganism Elimination Techniques

From this figure, considering the advantages and disadvantages of methods for purifying water from microorganisms, we have decided to opt for ozone technology. The overall objective of the scientific research is focused on Astana, the capital of the Republic of Kazakhstan, one of the Central Asian countries, with a population of 1,481.4 thousand. Drinking water is taken from the Vyacheslav reservoir and, to this day, is disinfected from harmful microorganisms using the chlorination method. However, the quality of the water remains very low. For example, there is an algae-like odor in the treated drinking water. To address this issue, we decided to conduct specialized scientific research at the Kazakh National Technical Research University named after K.I. Satbayev. The proposed research work, utilizing ozone technology, is expected to be an environmentally friendly, efficient, and cost-effective solution for purifying the Vyacheslav reservoir from microorganisms.

2. Materials And Methods

The methodology includes both experimental and theoretical analyses, leveraging advanced modeling techniques to simulate ozone-water interactions under varying environmental conditions.

Ozone technology is widely used for water purification from harmful microorganisms, and its effectiveness has been proven in numerous studies. Ozone has been shown to be highly effective in eliminating bacteria, viruses, and protozoa, including human gastrointestinal bacteria, norovirus, and adenovirus. For example, studies show that ozone breaks down in water without leaving residues and does not produce hazardous by-products during the disinfection process, making it a more environmentally friendly method compared to chlorination. Additionally, ozone improves the color and odor of water, while also removing organic and inorganic pollutants (Epelle et al., 2022; Golfinopoulos et al., 2024).

One of the main advantages of the ozonation method is its effectiveness against antibiotic-resistant bacteria. The growing issue of antibiotic resistance in global healthcare can be addressed, in part, by ozonation, as it plays an important role in combating this problem (Westover et al., 2022; Abdykadyrov et al., 2023; Kozhaspaev et al., 2016). However, ozone generation does have certain disadvantages, including high energy consumption and the potential formation of harmful compounds like bromates in some cases. The rapid decomposition of ozone in water also indicates its inefficiency for long-term disinfection (Gregov et al., 2023; Alhamzah et al., 2023).

To address these challenges, combining ozonation with coagulation and adsorption methods can enhance the effectiveness of water treatment. Such an approach helps reduce the amount of natural organic matter and improve water quality (Karwowska and Sperczyńska, 2023. Thus, while ozonation is an environmentally friendly and effective method, further research is needed to reduce energy costs and prevent the formation of harmful compounds for wider application (Karwowska et al., 2021; Ferreiro Santiso et al., 2021).

Ozone, as a powerful oxidizer, directly impacts microorganisms during water disinfection. It penetrates their cell walls and disrupts cellular structures, leading to the breakdown of DNA and other essential molecules, ultimately causing the death of microorganisms. Ozone's effect applies not only to bacteria but also to viruses, fungi, and parasites. Ozone's rapid decomposition in water makes it an efficient but short-term disinfectant, which may necessitate additional sterilization measures (Gregov et al., 2023; Karwowska and Sperczyńska, 2023).

The efficiency of this process depends on several factors, including the concentration of organic matter in the water, the ozone dosage, temperature, and treatment duration.

2.1 The Effect of Ozone on Microorganisms in Water Depending on Temperature

The impact of ozone on microorganisms is directly related to temperature, as the rate of ozone decomposition in water increases with rising temperatures. At lower temperatures, ozone decomposes more slowly, ensuring more effective elimination of microorganisms. However, at higher temperatures, its effectiveness decreases. This indicates the importance of considering temperature when using ozone as a disinfection agent (Table 1).

Table 1: The Effect of Ozone on Microorganisms in Water Depending on Temperature

Temperature (°C)	Ozone Decomposition Rate (High/Low)	Effectiveness Against Microorganisms (High/Low)
5	+	+++
10	+	+++
15	++	++
20	++	++
25	+++	+
30	+++	+
35	++++	++++

"+" – Low, "++" – Moderate, "+++" – High, "++++" – Very High

This Table 1 illustrates the relationship between temperature, the rate of ozone decomposition, and its effect on microorganisms in water. As the temperature increases, the decomposition rate of ozone also rises, which reduces its effectiveness in destroying microorganisms. At lower temperatures (from 5°C to 10°C), ozone decomposes slowly, maintaining high efficiency. However, when the temperature reaches 25°C and above, the rapid decomposition of ozone significantly reduces its ability to disinfect the water effectively. In such cases, additional methods may be needed to ensure complete disinfection.

2.2 The Effect of Ozone Dosage on Microorganisms in Water

The ozone dosage has a direct impact on the effectiveness of eliminating microorganisms in water. At lower doses (0.5-1.0 mg/L), the effect of ozone is weak, while increasing the dose (2.5-3.0 mg/L) significantly enhances its effectiveness. Thus, selecting the appropriate dosage during the ozonation disinfection process plays a crucial role in efficiently eliminating microorganisms (Table 2) (Abdykadyrov et al., 2024; Abdykadyrov et al., 2023).

Table 2: The Effect of Ozone Dosage on Microorganisms in Water

Ozone Dosage (mg/L)	0,5	1,0	1,5	2,0	2,5	3,0
Effectiveness Against Microorganisms (Low/Moderate/High)	+	+	++	++	+++	+++
"+" – Low, "++" – Moderate, "+++" – High,						

This Table 2 demonstrates the effect of ozone dosage on microorganisms in water. As the ozone dosage increases, its efficiency in eliminating microorganisms also improves. For instance, at a dosage of 0.5-1.0 mg/L, the effect of ozone is relatively low, while at 2.5-3.0 mg/L, its effectiveness significantly increases. This highlights the importance of selecting the appropriate ozone dosage to achieve effective water disinfection.

2.3 The Effect of Ozone on Microorganisms in Water Depending on Time

The impact of ozone on microorganisms in water is time-dependent. Over a short period, its effect is limited, but increasing the exposure time enhances the effectiveness of ozone. Therefore, the duration of exposure is a crucial factor in the complete elimination of microorganisms during the water disinfection process (Table 3).

Table 3: The Effect of Ozone on Microorganisms in Water Depending on Exposure Time

Exposure Time (minutes)	1	2	3	4	5	6
Effectiveness Against Microorganisms (Low/Moderate/High)	+	+	++	++	+++	+++
"+" – Low, "++" – Moderate, "+++" – High,						

This Table 3 illustrates the time-dependent efficiency of ozone in eliminating microorganisms in water. Over a short period (1-2 minutes), the effect of ozone is minimal, but as the exposure time increases (3-4 minutes), its effectiveness reaches a moderate level. Extended exposure (5-6 minutes) significantly enhances ozone's ability to destroy microorganisms, highlighting the critical role that time plays in the disinfection process.

2.4 The Efficiency of Ozone in Eliminating Microorganisms in Water Depending on pH Levels

The efficiency of ozone in destroying microorganisms in water is directly related to pH levels. At lower pH levels (4.0 - 5.0), ozone's effect on microorganisms is high, with an efficiency rate ranging between 95% and 99%. As the pH level increases (7.0 - 8.5), the disinfection effect of ozone decreases, with efficiency dropping to around 70% to 80%. Therefore, it is crucial to monitor and select the appropriate pH levels for the effective use of ozone (Table 4) (Epelle et al., 2022; Romanovski et al., 2024).

Table 4: Effectiveness of Ozone in Microorganism Removal Based on pH Levels

pH Level	Ozone Concentration (mg/L)	Exposure Time (min)	Microorganism Removal Efficiency (%)
4,0	0,2	5,0	99,9
4,5			98,7
5,0			95,6
6,0			89,2
7,0			80,1
7,5			75,4
8,0			72,3
8,5			70,0

This Table 4 clearly demonstrates the efficiency of ozone in eliminating microorganisms depending on pH levels. At lower pH levels (4.0 - 5.0), ozone's efficiency is high, ranging from 95% to 99%, as ozone stability increases, enhancing its disinfectant properties. At higher pH levels (7.0 and above), the decomposition of ozone accelerates, resulting in a reduction in its effectiveness, with the efficiency dropping to 70% to 80%. Overall, this highlights the importance of pH levels in effectively using ozone for water disinfection, as it directly influences both the contact time and efficiency of ozone.

2.5 The theoretical basis of the water ozonation process

To formulate a mathematical model of ozone diffusion in water, it is necessary to consider the equations that describe the main physico-chemical processes involved. This model includes aspects such as ozone diffusion, solubility, and chemical reactions. The following equations and principles are used to build the model.

The diffusion of ozone in water is described by the diffusion equation. If the concentration of ozone is denoted as a function of time and space, C(z,t), Fick's second law is applied (Berry et al., 2017; Presumido et al., 2022).

$$\frac{\partial C(z,t)}{\partial t} = D\frac{\partial^2 C(z,t)}{\partial z^2} \quad (1)$$

where: C(z,t) is the concentration of ozone as a function of time t and depth z (mol/m^3), D is the diffusion coefficient of ozone (m^2/s), z is the spatial coordinate (water depth), t is time (s). The solubility of ozone in water is described by Henry's law (Abdykadyrov et al., 2023).

$$C_{eq} = k_H \cdot P_{O3} \quad (2)$$

where: C_{eq} is the equilibrium concentration of ozone in water (mol/L), k_H is Henry's constant (mol/L·atm), PO_3 is the partial pressure of ozone in the gas phase (atm). Figure 2 below presents the graph showing the relationship between ozone's partial pressure and its equilibrium concentration in water according to Henry's law. The points on the graph indicate the solubility of ozone corresponding to each pressure level (Figure 2).

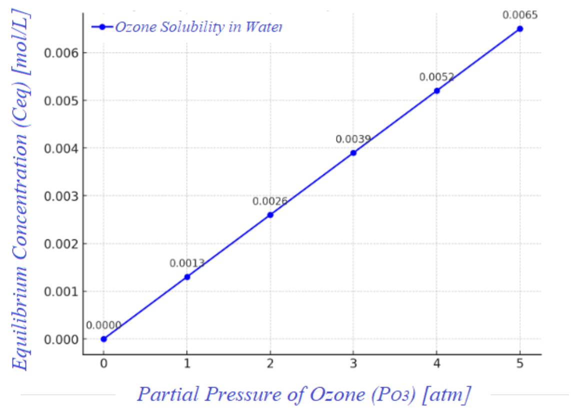


Figure 2: Ozone Solubility in Water vs Partial Pressure (Henry's Law)

In Figure 2, the relationship between the partial pressure of ozone (PO_3) and its equilibrium concentration in water (C_{eq}) according to Henry's law can be observed. As the partial pressure of ozone increases, its solubility in water also increases linearly. Additionally, the figure shows that at higher pressures, the concentration of dissolved ozone in water rises, indicating that more ozone can dissolve under greater pressure.

The chemical decomposition of ozone in water is described by the kinetic equation of a first-order reaction.

$$\frac{\partial C(z,t)}{\partial t} = -k_d \cdot C(z,t) \quad (3)$$

where: k_d is the rate constant for the chemical decomposition of ozone (s^{-1}), C(z,t) is the concentration of ozone at time t (mol/L).

The general equation for ozone transport, diffusion, and chemical reactions is given as follows:

$$\frac{\partial C(z,t)}{\partial t} = D\frac{\partial^2 C(z,t)}{\partial z^2} - k_d \cdot C(z,t) \quad (4)$$

This equation describes the diffusion and chemical decomposition (reaction) of ozone in water.

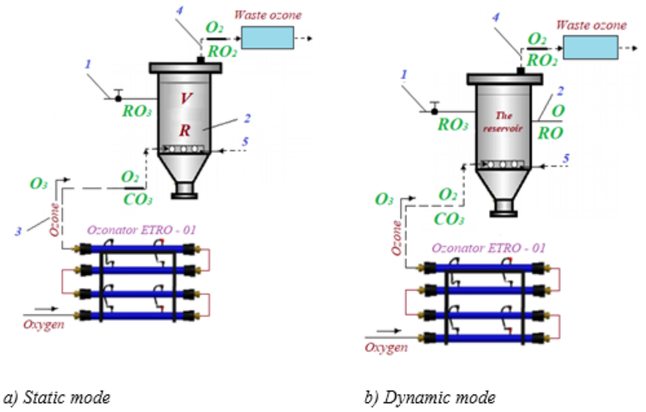
Initial and boundary conditions:

- *Initial condition:* At the initial time, the concentration of ozone in water is $C(z,0) = C_0$, where C_0 is the initial concentration.
- *Boundary conditions:* At the water surface $z = 0$, ozone diffusion is determined by the equilibrium between air and water, so $C(0,t) = C_{eq}$
- At a certain depth $z = L$, the ozone concentration may approach zero, thus $C(L,t) = 0$ (Chernykh et al., 2023; Berry et al., 2017; Alqahtani, 2021).

Solving such equations analytically can be challenging; therefore, numerical methods, such as the finite difference method or the Runge - Kutta method, are often used. These methods allow for calculating ozone concentration over time and space. The equations (1), (2), (3), and (4) described above form the core mathematical model for ozone transport and chemical reactions in water. This model enables the calculation of ozone concentration as a function of time and water depth, helping to evaluate the effectiveness of ozone in water purification.

2.6 Errors in Static and Dynamic Modeling of the Ozonator

To analyze the errors in the static and dynamic modeling of the ozonator, let's first draw its structural diagram (Figure 3). Upon closely examining Figure 3, we can see that the static and dynamic modeling methods are quite similar. However, if we compare the key parameters of this process, we can observe significant differences. Now, let's thoroughly compare and study these two cases.



Here, 1 – initial water; 2 – reservoir of ozonated and purified water, and its outlet; 3 – initial ozone concentration; 4 – residual ozone concentration; 5 – porous diffuser.

Figure 3: Structural diagram of the water ozonation process

Now, let's analyze the structural diagram of the water ozonation process shown in Figure 3, separately for each mode: static and dynamic.

a) For the static case:

$$G = G_0+G_R+G_B \quad (5)$$

$$G = [CO_3]\cdot Q_B\cdot T_k \quad (6)$$

$$G_0 = RO\cdot V \quad (7)$$

$$G_R = [RO_3]\cdot V \quad (8)$$

$$Q_B = [RO_3] = Q\cdot T_k \quad (9)$$

$$Q_B = [CO_3]\cdot T_k= RO\cdot V + RO_3\cdot V + [RO_3]\cdot Q_B\cdot T_k \quad (10)$$

$$\eta = G - G_B / G = 1 - G_B/ G = 1 - [RO_3]/ [CO_3] \quad (11)$$

$$T_k\cdot[CO_3]\cdot Q_B\, \eta / V = RO + RO_3 \quad (12)$$

$$D_{O3} =T_k\cdot [CO_3]\cdot Q_B / V = RO + RO_3/ \eta \quad (13)$$

$$RO = \eta\, D_{O3} - RO_3 \quad (14)$$

b) For the dynamic case:

$$G = G_0+G_R+G_B \quad (15)$$

$$G = [CO_3]\cdot Q_B \quad (16)$$

$$G_0 = RO\cdot Q \quad (17)$$

$$G_R = [RO_3]\cdot Q_B \quad (18)$$

$$Q_B[CO_3]= RO\cdot Q + RO_3\cdot Q + [RO_3]\cdot Q_B \quad (19)$$

$$\eta = G - G_B / G = 1 - G_B/ G = 1 - [RO_3]/ [CO_3] \quad (20)$$

$$[CO_3]\cdot Q_B\, \eta / Q = RO + RO_3 \quad (21)$$

$$D_{O3} = [CO_3]\cdot Q_B / Q = RO + RO_3/ \eta \quad (22)$$

$$RO = \eta\, D_{O3} - RO_3 \quad (23)$$

Here, G refers to the initial amount of ozone introduced into the water; G_O is the amount of ozone used for the oxidation of harmful microorganisms and chemical compounds; G_R is the amount of residual ozone after the reaction; G_B is the amount of residual ozone after the technological process; Q is the amount of purified water coming out of the reservoir, in m^3/h; V is the total volume of purified water, in m^3/h; Q_B is the consumption of the ozone-air mixture during the technological process, in Nm^3/h; R_O is the ozone absorption of the initial contaminated water before the contact chamber, in mg/l; $[CO_3]$ is the concentration of ozone in the mixture (ozone-enriched air) after the ETRO - 01 ozonator, in g/Nm^3; $[RO_3]$ is the concentration of the ozone-air mixture in the reservoir after the technological process, in g/Nm^3; η is the efficiency (E) of ozone use during the process; Do_3 is the ozone concentration, in g/m^3; Tk is the contact time of the ozone with the water in the reservoir, in minutes.

The main error in the static modeling example above is the inaccuracy of the contact time in the contact reservoir because the residual ozone concentration $[RO_3]$ is independent. Since the saturation process occurs, it is clear that the ozonated water has an integral nature. Therefore, the contact time cannot be determined using the formula $T_k = 60\ (V/Q)$. This expression is applied during dynamic experiments. However, at any given time, it is not possible to supply the ozone-air mixture from the ETRO - 01 ozonator to the purified water $[RO_3] = 0$ (η=1). That is, the efficiency (E) is not characterized during the dynamic modeling of the technological process in a stationary dynamic mode. The ETRO - 01 ozonator device is based on electrical corona discharge. The ozonator's voltage is 15 kV, with a power of 0.8 kW, and the power supply frequency is 50 Hz. Its capacity is 10 g/m^3.

The research involves theoretical and experimental studies using a Python-coded mathematical model to simulate ozone diffusion and disinfection dynamics. The ETRO-02 ozonator was calibrated and operated under specified parameters (voltage: 18 kV; power: 2 kW) to test water samples from the Vyacheslav Reservoir. Parameters such as ozone concentration, exposure time, and pH levels were systematically varied to analyze disinfection efficiency.

3. Results And Discussions

Based on the aforementioned foreign and domestic research studies, we, in collaboration with the "Kazakh National Technical Research University named after K.I. Satbayev" and the "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers," decided to eliminate harmful microorganisms present in the surface water of the Vyacheslav reservoir using ozone technology. For conducting the scientific research, we developed a pilot ozonator device, type ETRO-02, based on electrical corona discharge with a voltage of 18 kV, a power of 2 kW, a frequency of 50 Hz, and a capacity of 30 g/m^3. This device is protected by a copyright certificate from the Ministry of Justice of the Republic of Kazakhstan (Abdykadyrov et al., 2024). The general appearance of the device is shown in Figure 4 below.

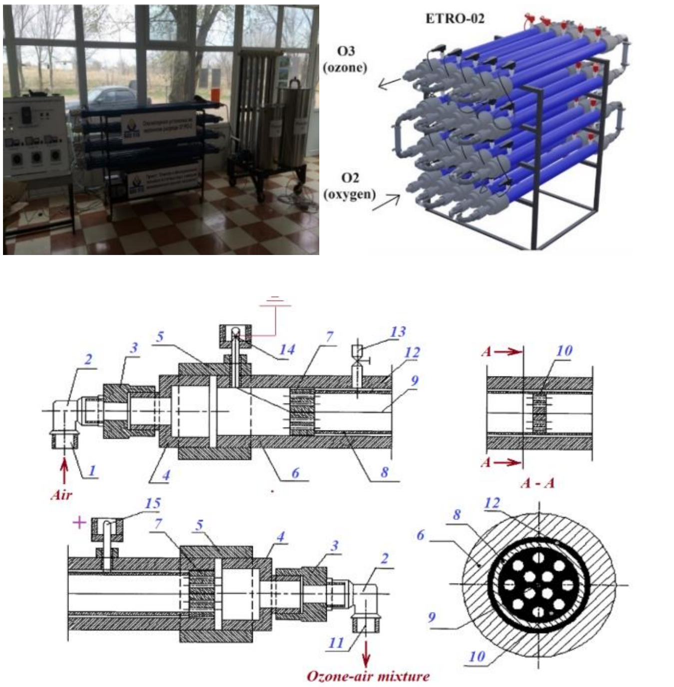


Figure 4: ETRO - 02 pilot-based ozonator installation based on electrical corona discharge

Device and principle of operation of the ozonator:

i. Device. The figure shows the diagram of one section of the ozonator and the A-A cross-section. In total, there are 20 units in the installation, connected sequentially in the form of stages. Each of these stages is made of high-quality dielectric polymer material (6). 1 - inlet for air intake; 2 - fitting (brass); 3 - nozzle; 4 - adapter; 5 - coupling (plastic); 6 - casing (plastic); 7 - fluoroplastic disc with a diameter of 40 mm, serving as the main dielectric support for the negative electrode, with holes; 8 - hollow cylindrical positive electrode (steel); 9 - negative electrode (nichrome); 10 - fluoroplastic disc with a diameter of 35 mm, serving as an intermediate support for the negative electrode (2 pieces at specified distances, with holes); 11 - outlet for the ozone-air mixture; 12 - cavity filled with nitrogen for cooling the electrode; 13 - valve for pumping gaseous nitrogen; 14 - clamp for connecting the negative electrode to the power source; 15 - clamp for connecting the positive electrode to the power source.

ii. Operation of the device. A special rectifying device was developed to supply the ozonator with a high voltage of 18 kV. When 18 kV is applied, a corona discharge occurs on the electrodes of the ozonator, creating favorable conditions for the formation of triatomic oxygen, i.e., ozone (O3). Using a compressor, air is fed into the inlet (1) of the ozonator, then, passing through the fitting (2), nozzle (3), adapter (4), coupling (5), and the holes in the first main fluoroplastic support disc (7), it enters the inter-electrode space, where the ozone generation process occurs. The resulting ozone-air mixture then passes through the holes of the intermediate fluoroplastic supports (10), the holes of the second main fluoroplastic support disc (7), coupling (5), adapter (4), nozzle (3), and fitting (2), and is directed to the outlet (11) of the ozonator. The level of technology available in the Republic of Kazakhstan allows for the production of this device.

3.1 Experimental Research Methods for Purifying Harmful Microorganisms in Water

To conduct experimental research methods for purifying harmful microorganisms in water, we first collected water from the Vyacheslav Reservoir and carried out laboratory analysis of the water's composition, specifically focusing on microorganisms. The results of the study can be observed in Table 5 and Figure 5 below.

Table 5: Composition of Initial Non-Ozonated Water Taken from Vyacheslav Reservoir

No	Name of Indicators	Units of Measurement	Norms according to SanPiN 3.02.002.04 and GOST 2874	Recommended guidelines by WHO (1994)	The initial content of microorganisms in the water
1	The number of microorganisms in 1 ml (total microbial count: total number of bacteria in 1 ml)	units/ml	No more than 50		525
2	Total coliform bacteria	Number of bacteria per 100 ml	Absent	Absent	121
3	Thermotolerant bacteria	Number of bacteria per 100 ml	Absent	Absent	47
4	Coliphages	PFU per 100 ml	Absent	Absent	55
5	Clostridium spores	Number of bacteria per 20 ml	Absent	Absent	10
6	Parasitological studies: Giardia cysts	Cysts per 50 ml	Absent	Absent	35

From this table, we can observe the following: the number of microorganisms per 1 ml is 525, the number of total coliform bacteria per 100 ml is 121, the number of thermotolerant bacteria per 100 ml is 47, the number of coliphages per 100 ml (PFU) is 55, the number of Clostridium spores per 20 ml is 10, and parasitological studies show Giardia cysts in 50 ml.

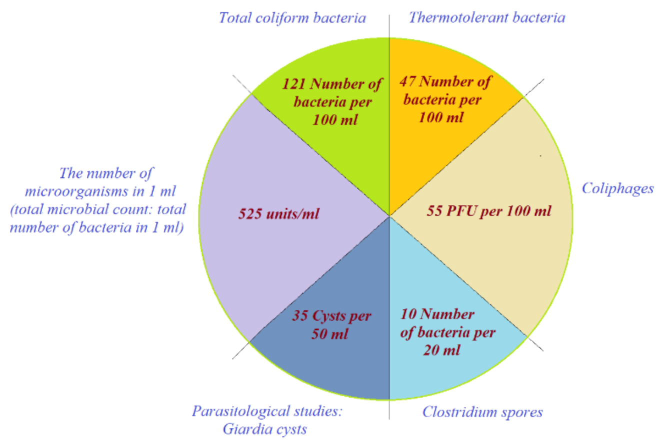
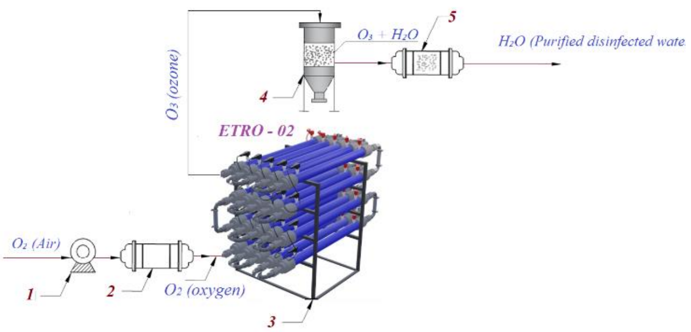


Figure 5: Initial Indicators of Microorganisms in Non-Ozonated Water

From this figure and the table, the following observations can be made: 1) The presence of 525 microorganisms per 1 ml indicates bacterial contamination of the water, which may affect the human gastrointestinal system; 2) The presence of 121 coliform bacteria per 100 ml suggests fecal contamination, which can lead to intestinal diseases; 3) The presence of 47 thermotolerant bacteria per 100 ml indicates fecal pollution, posing a risk of intestinal infections; 4) The presence of 55 coliphages per 100 ml suggests the risk of viral contamination, which may cause diseases related to viruses; 5) The presence of 10 Clostridium spores per 20 ml indicates anaerobic bacterial contamination, potentially leading to serious illnesses such as botulism; 6) The presence of Giardia cysts in 50 ml suggests the risk of intestinal parasites, which can lead to diseases like diarrhea.

To address these issues, we decided to disinfect and purify the water in the reservoir using ozone technology. In this study, specifically to eliminate harmful microorganisms, the ETRO-02 pilot ozonator device, based on electrical discharge, was used to study the water purification process. Using this device, a technological scheme for water disinfection was developed (Figure 6).



1 – Compressor for supplying air or oxygen; 2 – Air drying and preparation unit; 3 – Pilot ETRO-02 ozonator device based on electrical discharge; 4 – Reservoir for disinfecting and purifying water with ozone; 5 – Membrane filter load made of fine sand.

Figure 6: Technological diagram of the process of eliminating harmful microorganisms using ozone technology

The difference between ozone technology and other oxidizing agents can be observed in the following Table 6 (Abdykadyrov et al., 2024). The table shows that at a normal temperature range of 20°C - 240°C and a pH of 6.8, harmful microorganisms in water are oxidized and neutralized by 95% - 98%.

Table 6: Disinfection Methods and Their Efficiency in Eliminating Harmful Microorganisms

Disinfection methods	The names of harmful microorganisms				
	Total coliform bacteria	Thermotolerant bacteria	Coliphages	Clostridium spores	Parasitological studies: Giardia cysts
Ozone (O_3)	99 - 100% (within 2 - 4 minutes)	98 - 99% (around 3 - 5 minutes)	90 - 100% (within 5 - 10 minutes)	85 - 90% (longer exposure, about 10 - 15 minutes)	99 - 100% (10 -15 minutes)
Chloroform acid (HOCl)	99 - 100% (30 seconds - 1 minute)	95 - 99% (1-2 minutes)	90 - 100% (5-10 minutes)	70 - 80% (10 - 30 minutes)	90 - 95% (10 -15 minutes)
Chlorine dioxide (ClO_2)	99 - 100% (1 -2 minutes)	97 - 99% (about 3-5 minutes)	95 - 100% (5-10 minutes)	80 - 90% (10 - 15 minutes)	95 - 100% (10 - 15 minutes)
Hypochlorite ions OCl^-	99 - 100% (1-5 minutes)	95 - 99% (3-5 minutes)	90 - 100% (5-15 minutes)	70 - 80% (longer exposure, about 20-30 minutes)	85 - 95% (10 -20 minutes)
Dichloramine ($NHCl_2$)	98 - 100% (5 -10 minutes)	95 - 98% (10 -15 minutes)	90 - 95% (10 -20 minutes)	60 - 75% (longer than 30 minutes)	85 - 90% (15 -20 minutes)
Chloramine (NH_2Cl)	90 - 99% (longer exposure, 15 -30 minutes)	85 - 90% (longer than 30 minutes)	80 - 90% (longer exposure, 20-30 minutes)	50 - 70% (very long exposure)	80 - 85% (longer exposure, more than 30 minutes)

The advantages of ozone (O_3) over other disinfection methods listed in the table are as follows:

- **High efficiency** - ozone is a very powerful oxidizing agent, making it highly effective at destroying bacteria, viruses, fungi, and other pathogens. It can eliminate total coliform bacteria by 99-100% within 2-4 minutes, which provides faster results compared to other methods;

- **No chemical residues** - when ozone decomposes, it only turns into oxygen molecules (O_2). This ensures that no chemical residues remain in water or air after using ozone. Unlike chlorine-based disinfection methods (e.g., chlorine dioxide or hypochlorite ions), ozone leaves no harmful residues;

- **Broad-spectrum effect** – ozone is effective not only against bacteria but also against viruses, fungi, and spores. It can destroy thermotolerant bacteria and coliphages by 90-100%, which is higher than some other methods;

- **Fast reaction time** - ozone disinfection works faster than other methods. It can effectively kill microorganisms within a few minutes, such as eliminating coliform bacteria within 2-4 minutes, which is significantly faster than slower methods like chloramine;

- **Effectiveness against resilient microorganisms** - ozone can affect some resilient microorganisms, such as Clostridium spores, which are more resistant to other disinfection methods. Ozone's effectiveness against Clostridium spores is 85-90%, which is higher than many other methods;

- **Environmentally friendly** - *o*zone is an environmentally safe disinfection method as its by-products do not harm the environment, and no toxic chemicals are released during its use.

Thus, ozone's main advantages are its speed, high efficiency, environmental safety, and lack of residues.

Based on Table 5, the harmful microorganisms found in the raw water from the reservoir do not comply with the sanitary rules and regulations 3.02.002.04 and GOST 2874. For this purpose, we conducted experimental research in two cases: 1) according to the amount of ozone (C, mg/L); 2) the disinfection process based on time (t, minutes). That is, the dynamics of purification of microorganisms and bacteria in water using ozone were studied. The table shows the elimination of microorganisms in water over time due to the effect of ozone, and these results are compared with the maximum allowable limits established by sanitary standards. The results of the research can be observed in Tables 7 and 8 below.

Table 7: The Effect of Ozone Concentration on the Elimination of Microorganisms and Bacteria in Water

The names of microorganisms and bacteria found in the water	The amount of microorganisms in the raw water	The concentration of ozone CO, mg/L (disinfection time 20 minutes)					The maximum allowable concentration established by sanitary rules and regulations 3.02.002.04
		0,2 mg/L	0,4 mg/L	0,6 mg/L	0,8 mg/L	1,0 mg/L	
Total coliform bacteria	121 Number of bacteria per 100 ml	98	65	38	17	0	Must not be present in drinking water
Thermotolerant bacteria	47 Number of bacteria per 100 ml	28	15	5	0	0	Must not be present in drinking water

Table 7 (Cons): The Effect of Ozone Concentration on the Elimination of Microorganisms and Bacteria in Water

Coliphages	55 PFU per 100 ml	33	15	8	3	0	Must not be present in drinking water
Clostridium spores	10 Number of bacteria per 20 ml	5	2	0	0	0	Must not be present in drinking water
Parasitological studies: Giardia cysts	35 Cysts per 50 ml	15	9	1	0	0	Must not be present in drinking water
The number of microorganisms in 1 ml (total microbial count: total number of bacteria in 1 ml)	525 units/ml	375	198	96	45	0	The total number of microbes must not exceed 50

This table demonstrates the effect of ozone concentration on the elimination of microorganisms and bacteria found in water. As the ozone concentration increases (from 0.2 mg/L to 1.0 mg/L), the number of microorganisms and bacteria gradually decreases and eventually is completely eliminated. For example, at a concentration of 1.0 mg/L, all coliphages, thermotolerant bacteria, and Giardia cysts are destroyed. These data confirm the effectiveness of water purification using ozone and ensure compliance with sanitary standards, which require that no microorganisms be present in drinking water.

Table 8: The dynamics of purification of microorganisms and bacteria in water using ozone

The names of microorganisms and bacteria found in the water	The amount of microorganisms in the raw water	The destruction of microorganisms in water over time (ozone concentration of 1 mg/L).					The maximum allowable concentration established by sanitary rules and regulations 3.02.002.04
		4 minutes	8 minutes	12 minutes	16 minutes	20 minutes	
Total coliform bacteria	121 Number of bacteria per 100 ml	95	77	38	15	0	Must not be present in drinking water
Thermotolerant bacteria	47 Number of bacteria per 100 ml	28	12	8	0	0	Must not be present in drinking water
Coliphages	55 PFU per 100 ml	35	12	4	0	0	Must not be present in drinking water
Clostridium spores	10 Number of bacteria per 20 ml	5	1	0	0	0	Must not be present in drinking water
Parasitological studies: Giardia cysts	35 Cysts per 50 ml	18	8	2	0	0	Must not be present in drinking water
The number of microorganisms in 1 ml (total microbial count: total number of bacteria in 1 ml)	525 units/ml	327	168	85	38	0	The total number of microbes must not exceed 50

This table shows the dynamics of microorganism and bacteria elimination in water over time when the ozone concentration is 1 mg/L. In the first 4 minutes, the number of microorganisms significantly decreases, and by 20 minutes, they are completely eliminated. For instance, within 20 minutes, total coliform bacteria, thermotolerant bacteria, coliphages, and Giardia cysts are entirely destroyed. This demonstrates the high efficiency of water purification using ozone and confirms that, according to sanitary standards, no microorganisms should be present in drinking water.

3.2 Mathematical Analysis of Ozone-Based Water Disinfection Processes

The elimination of microorganisms found in the initial water in storage through ozone is based on the kinetics of chemical reactions. In this process, the rate of interaction between ozone and microorganisms plays a crucial role. The main objective of the modeling is to formulate equations that describe the number of microorganisms depending on time and ozone concentration. The following variables and parameters are used in the study model: 1) $N(t)$ – the number of microorganisms over time; 2) CO – ozone concentration (mg/L); 3) k – the rate coefficient of ozone's disinfecting effect (disinfection efficiency constant); 4) t – disinfection time (minutes); 5) N_0 – the initial number of microorganisms. The dynamics of microorganism elimination can be calculated using the expression (24) below. This fundamental model describing the elimination of microorganisms is an exponential decay model based on first-order reactions.

$$N_{(t)} = N_o \cdot e^{-k \cdot C \cdot t} \quad (24)$$

Here, $N(t)$ is the number of microorganisms after time t, N_0 is the initial number of microorganisms, k is the disinfection coefficient of ozone, C is the ozone concentration, and t is the disinfection time. This model describes the effect of ozone concentration and time on the disinfection process. The higher the concentration or the longer the time, the fewer microorganisms remain. If we consider the variation in ozone concentration while keeping time constant, then equation (24) can be rewritten as follows:

$$N(C) = N_o \cdot e^{-k \cdot C} \quad (25)$$

Here, only the ozone concentration changes, while time t remains constant. Now, if the ozone concentration remains constant while time changes, equation (24) can be written as follows:

$$N_{(t)} = N_o \cdot e^{-k \cdot t} \quad (26)$$

This equation (26) describes how the concentration of microorganisms decreases over time. In general, the mathematical model of the water disinfection process with ozone in Vyacheslav Reservoir allows for the evaluation and control of the water purification efficiency. The model characterizes the impact of ozone concentration and time on the elimination of microorganisms and is used to optimize water treatment processes. This method contributes to the safe and efficient purification of water resources. Let's write the algorithmic code for the study using the Python programming language based on the experimental research work provided in Tables 7 and 8 (Figure 7).

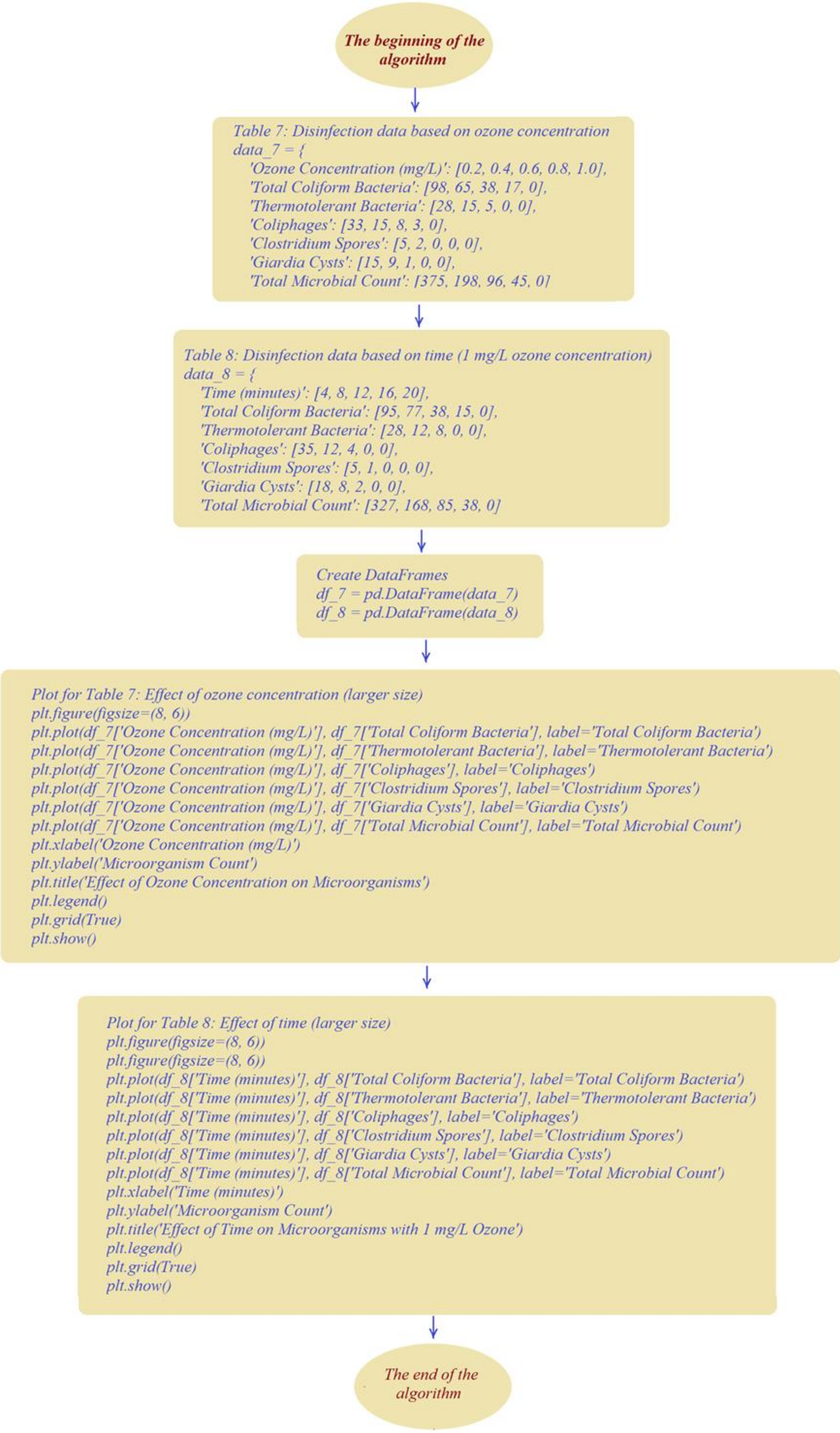


Figure 7: The algorithm of the effect of ozone concentration and time on microorganisms

The diagram presented in Figure 7 describes the disinfection effect on microorganisms depending on ozone concentration and time. In the first part, a table shows how ozone concentration (mg/L) affects microorganisms such as total coliform bacteria, thermotolerant bacteria, phages, spores, and cysts. The second table illustrates the impact of time (in minutes) on microorganisms at an ozone concentration of 1 mg/L. Now, from this algorithm, we can observe how ozone concentration affects harmful microorganisms in the water, as shown in Figure 8.

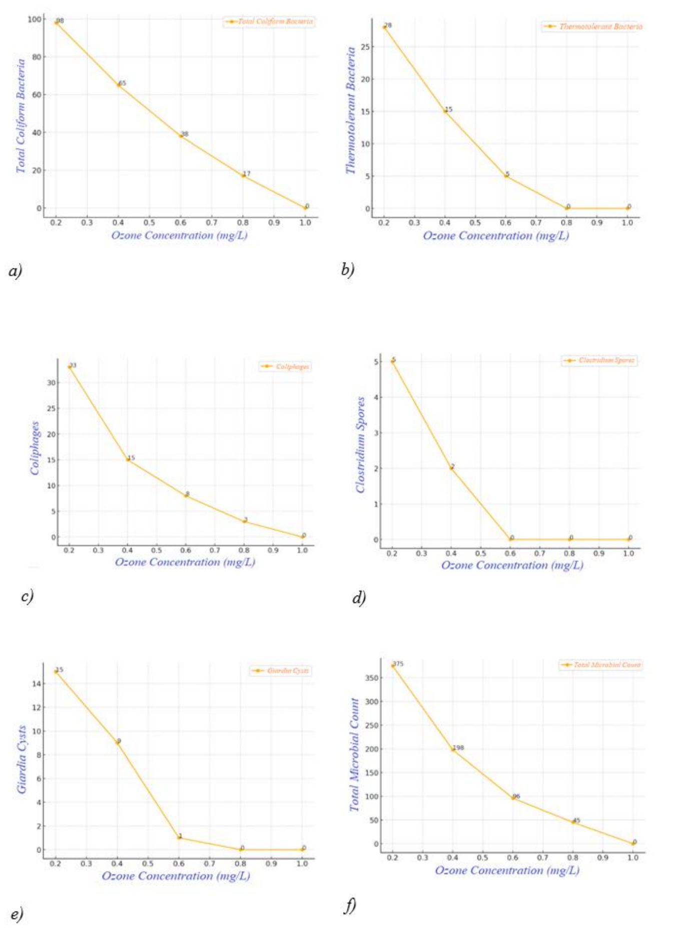


Figure 8: The Effect of Ozone Concentration on Microorganisms Found in Water

From Figures 7 and 8, we can observe the reduction in microorganism counts at different ozone concentration levels. Specifically: a) *Total Coliform Bacteria* - at 0.2 mg/L ozone concentration, their count is 98, but at 1.0 mg/L concentration, they are completely eliminated (0); b) *Thermotolerant Bacteria* - at 0.2 mg/L concentration, their count is 28, but from 0.8 mg/L concentration, they are fully eliminated; c) *Coliphages* - at 0.2 mg/L concentration, their count is 33, but at 1.0 mg/L, it decreases to 0; d) *Clostridium Spores* - at 0.2 mg/L concentration, their count is 5, and from 0.6 mg/L concentration, they are completely eliminated; e) *Giardia Cysts* - at 0.2 mg/L concentration, their count is 15, and at 1.0 mg/L, they are fully eliminated; f) *Total Microbial Count* - at 0.2 mg/L concentration, their count is 375 units, and at 1.0 mg/L, it reduces to 0. The elimination dynamics of each microorganism accelerate at higher ozone concentrations. A sharp decrease in microorganism counts is observed starting from a concentration of 0.6 mg/L. At 1.0 mg/L concentration, all microorganisms are fully eliminated, demonstrating the effectiveness of ozone's disinfection effect. These data indicate that increasing the ozone concentration to 1.0 mg/L is sufficient to eliminate all microorganisms.

3.3 Analysis of the Scientific Research

According to the scientific research, among the water disinfection methods, chloramine is widely used in many countries for water purification, especially for disinfecting water that needs to be stored in water systems for a long period of time. This makes it a suitable method for comparison with ozone. The efficiency of ozone technology in eliminating harmful microorganisms in water stands out with several advantages compared to other disinfection methods. First, ozone eliminates total coliform bacteria within 2 - 4 minutes at a 99 - 100% rate, which is much faster than other methods (e.g., chloramine takes 15 - 30 minutes). Second, ozone leaves no harmful residues because it simply decomposes into oxygen, whereas chlorine-based methods produce hazardous by-products. Third, ozone is effective against all types of microorganisms, including bacteria, viruses, fungi, and spores, with a destruction efficiency of up to 85-90%. For example, ozone can eliminate Clostridium spores by 85 - 90% within 10 - 15 minutes, which is a higher rate compared to other methods. Additionally, ozone can be applied over a wide range (with an efficiency of 95 - 99% at pH levels of 4.0 - 5.0) and is environmentally friendly. It also performs effectively under high temperatures and pressure. Overall, ozone technology demonstrates high efficiency in rapidly and completely eliminating harmful microorganisms in water. The results of the research, particularly the time-dependent efficiency of ozone and chloramine in microorganism elimination, can be observed in Figure 9 below.

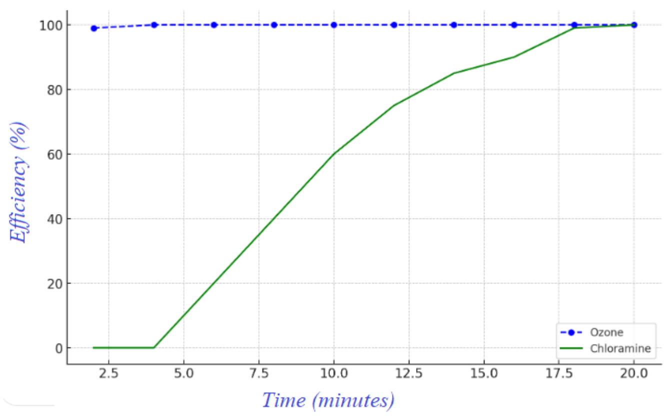


Figure 9: The Time-Dependent Efficiency of Ozone and Chloramine in Microorganism Elimination

This figure compares the time-dependent efficiency of ozone and chloramine methods in eliminating microorganisms. *Ozone Method* - as shown in the graph, ozone eliminates 99 - 100% of microorganisms within 2-4 minutes. Ozone acts very quickly, achieving high efficiency in a short period. After 4 minutes, ozone completely destroys the microorganisms, reaching maximum effectiveness. This is due to ozone's strong oxidizing properties and its rapid action. *Chloramine Method* - the chloramine method requires more time to eliminate microorganisms. The graph shows that up to 10 minutes, the efficiency increases slowly, reaching only 75%. Only after 16 minutes does it reach 90%, and full elimination (100%) is achieved after 20 minutes. This indicates that chloramine acts more slowly than ozone and requires more time to achieve the same level of disinfection. In summary, the ozone method provides faster and more efficient results in eliminating microorganisms. Compared to chloramine, ozone acts much quicker, allowing for complete disinfection in a shorter time.

4. Conclusion

This study confirms the effectiveness of ozone technology as a powerful and environmentally friendly solution for water disinfection. The research on harmful microorganisms in the Vyacheslav Reservoir demonstrated ozone's superior efficiency compared to conventional methods, such as chloramine. Ozone eliminates total coliform bacteria within 2–4 minutes at a rate of 99–100%, significantly outperforming chloramine, which requires 15–30 minutes to achieve similar results.

A key environmental advantage of ozone is its decomposition into oxygen after use, leaving no harmful residues, unlike chlorine-based methods that produce hazardous by-products. Additionally, ozone effectively targets a wide range of microorganisms, including bacteria, viruses, fungi, and spores. For instance, ozone was shown to destroy Clostridium spores by 85–90% within 10–15 minutes, a significantly higher efficiency than other methods.

Ozone technology operates effectively under diverse conditions, including high temperatures and pressures, and achieves a disinfection efficiency of 95–99% at pH levels of 4.0–5.0. Its rapid action and adaptability make it a practical solution for both industrial and domestic water systems. While chloramine is commonly used for long-term water storage, it requires longer exposure times compared to ozone, which can eliminate harmful microorganisms in just a few minutes.

At an ozone concentration of 1.0 mg/L, complete disinfection of all harmful microorganisms was achieved within 20 minutes, meeting sanitary standards. These findings highlight ozone technology as a reliable, efficient, and sustainable method for water purification, particularly for addressing environmental and public health challenges.

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