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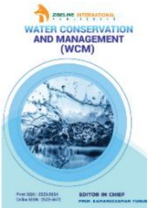

RESEARCH ARTICLE

# RESEARCH ON THE PROCESS OF DETOXIFYING AND PURIFYING HARMFUL COMPOUNDS IN GROUNDWATER USING A PILOT AUTONOMOUS UNIT

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## ABSTRACT

This scientific work is focused on detoxifying and purifying harmful compounds in the groundwater of the Talgar district, Almaty region, using a pilot autonomous complex unit. The groundwater in the district contains heavy metals, chemical compounds, and microorganisms that pose a threat to human health and the environment. During the research, comprehensive purification methods for water detoxification and purification were considered. A pilot ETRO-02 ozonator unit, based on a special electrical corona discharge, was developed for the purification system. Filtration methods and UV radiation were also applied. The research results aim to improve the quality of groundwater and make it suitable for use in autonomous drinking water systems. During the experimental work, the efficiency of the water purification unit, its parameters, and their impact on water quality were determined. This research is an important step towards providing clean and safe drinking water in rural and urban areas. Comprehensive studies were conducted to determine the effects of ozone dose, contact time of the treated water with the ozone-air mixture, water temperature, concentration of pollutants, filtration rate, iron, manganese, and the degree of water disinfection according to the sanitary rules and regulations (2.1.4.1074-01). The ozone dose ranged between 1.5 mg/l, the contact time with the ozone-air mixture between 5 to 20 minutes, the water temperature between 9 to 15ºC, and the filtration rate between 8 to 15 m/hour. As a result, the concentration of iron significantly decreased with increasing oxidation time, from an initial value of approximately 1.4 mg/l to about 0.1 mg/l within 20 minutes. The concentration of manganese also decreased, albeit at a slower rate, from an initial value of 0.2 mg/l to about 0.03 mg/l within 20 minutes. This demonstrated that heavy metals could be effectively removed from water over a prolonged period using ozone. Additionally, the initial water contained 17 general microbial count and a coliform index of 1575, which were completely eliminated after passing through the purification unit, meeting the sanitary standards (SanPiN 2.1.4.1074-01). Moreover, data from the experiments were processed using SMath Solver and Python, and an algorithmic code was written.

**KEYWORDS**

Groundwater, harmful compounds, pilot autonomous unit, detoxification, purification process, drinking water systems, environmental safety, water resources management

## 1. INTRODUCTION

Groundwater is an important natural resource used as drinking water in many rural and urban areas (Carrard et al., 2019; Khatri and Tyagi, 2015; Chaudhuri, and Roy, 2016). However, groundwater often contains various harmful contaminants (Sinha Ray and Elango, 2019; Ezugwu, 2015). That can be detrimental to human health and ecosystems. These contaminants include heavy metals, chemical compounds, and microorganisms (Priya et al., 2022). To address this issue, it is crucial to research and develop effective and safe methods for groundwater purification.

The aim of this study is to investigate the process of detoxifying and purifying harmful compounds in groundwater using a pilot autonomous unit. Autonomous units can be widely used in rural and remote areas because they are not dependent on electrical power and can operate independently (Peter-Varbanets et al., 2009).

The study will examine the efficiency of the unit, the detoxification methods, the parameters of the purification process, and their impact on groundwater quality. Additionally, the research results will allow for the assessment of the capabilities of autonomous units and their application in real-world conditions.

This research is an important step towards protecting the health and improving the quality of life of local residents by providing them with clean and safe drinking water.

### 1.1 Research Object

The object of this research is the groundwater from exploration and operational wells located in the northeast outskirts of Talgar city, Almaty region. These waters require pre-treatment to meet the requirements of sanitary rules and regulations 2.1.4.1074-01. In the laboratory setup, the optimal parameters for the technological processes (iron removal,

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manganese removal, and water detoxification) were determined experimentally. These parameters include ozone dose, contact time with the ozone-air mixture, filtration rate, and residual ozone concentration. These parameters ensure the quality of groundwater necessary for use in autonomous drinking water systems according to the "oxidation-filtration" scheme. A groundwater treatment technology and a technological unit with a capacity of 5 $m^3$/hour were developed for this purpose. This unit is designed to create an autonomous drinking water system.

The research also highlights the potential for creating autonomous drinking water systems for socially significant institutions (kindergartens, schools, hospitals, etc.) based on groundwater sources. Compared to surface water, groundwater is much less susceptible to technogenic pollution and seasonal changes in chemical and bacteriological composition. However, groundwater sources intended for drinking water must meet the quality requirements of sanitary rules and regulations 2.1.4.1074-01. For instance, analysis of the groundwater layer from wells in rural areas showed high levels of iron, manganese, and coliform bacteria. Thus, there is a need for additional purification and detoxification of groundwater to ensure its quality. The technology developed is based on the "oxidation-filtration" combined method using ozone as an oxidizing agent, which is not only a strong oxidizer but also possesses high bactericidal properties.

## 2. Materials and Methods

When selecting a method for groundwater purification, several factors need to be considered the initial quality of the water, the types of contaminants, the purification goals, and the economic and technical feasibility (Schwartz and Zhang, 2024; Sundaram et al., 2009). Taking into account the advantages and disadvantages of each method, general recommendations are provided (Table 1):

**Table 1:** Features and Disadvantages of Groundwater Purification Methods (Schwartz and Zhang, 2024; Abdykadyrov et al., 2023)

| № | Groundwater Purification Method | Features | Disadvantages |
|---|---|---|---|
| 1 | Mechanical Filtration (Nyer, 1992) | Removes dirt, clay, and other solid particles. Simple and cheap method. | Does not remove dissolved substances. Effective against only certain types of contaminants. Requires regular maintenance. |
| 2 | Chemical Treatment (Mohr et al., 2007) | Effective against chemical compounds and microorganisms. Wide range of applications. | Can introduce residual chemicals into the water. Requires careful handling and safety measures. |
| 3 | Ozone Treatment (Abdykadyrov et al., 2023; Draginsky,2007) | Strong oxidizer, effective against bacteria, viruses, and organic substances. Does not leave residuals. | Requires special equipment and trained personnel. Can be costly. |
| 4 | Ultraviolet Treatment (Abdykadyrov et al., 2023; Afriani and Trijoko, 2020). | Effective against microorganisms. Does not introduce chemicals into the water. | Limited effectiveness on non-biological contaminants. Requires clean water for maximum effectiveness. |
| 5 | Activated Carbon Filtration (Kozhaspaev N., et al., 2016; Lu et al., 2016; Zhang et al., 2024) | Effective against organic compounds and chlorine. Improves taste and odor. | Not effective against heavy metals. Requires regular replacement. |
| 6 | Ion Exchange (Hailu, 2019). | Effective against metals and minerals. Long-lasting method. | Requires regeneration with chemicals. Not effective against all types of contaminants. |

Based on the features and disadvantages of the methods presented in Table 1, it is possible to choose an effective method for groundwater purification.

When selecting a method for groundwater purification, several factors need to be considered: the initial quality of the water, the types of contaminants, the purification goals, economic feasibility, and technical capabilities. Taking into account the advantages and disadvantages of each method, general recommendations are as follows:

- *Mechanical Filtration:* This method is suitable for initial purification because it removes solid particles from the water. However, it is insufficient on its own, so it is best used in combination with other methods;
- *Chemical Treatment:* This method is highly effective if the water contains a large amount of chemical compounds or bacteria. However, the cost of chemical reagents and their impact on the taste and odor of the water should be considered;
- *Ozone Oxidation:* Widely used due to its strong oxidizing properties and high bactericidal effectiveness. Ozone can disinfect water and remove many contaminants. This method is particularly effective when protection against bacteria and viruses is needed. However, the cost of the equipment and the complexity of ozone generators should be considered;
- *Ultraviolet Disinfection:* Effective and environmentally friendly if the main concern is protection against bacteria and viruses. This method does not require chemical reagents, but the water must be highly transparent;
- *Activated Carbon Filtration:* Effective for removing organic compounds, chlorine, and odors. It is best used in combination with other methods, as it cannot remove bacteria and some chemical substances;
- *Ion Exchange:* Effective for removing hardness and metal ions (e.g., iron and manganese) from water. However, this method is costly and requires additional reagents.

Taking into account the advantages and disadvantages of these methods, we chose to combine them. Therefore, in the future, a comprehensive approach is recommended (Figure 1).

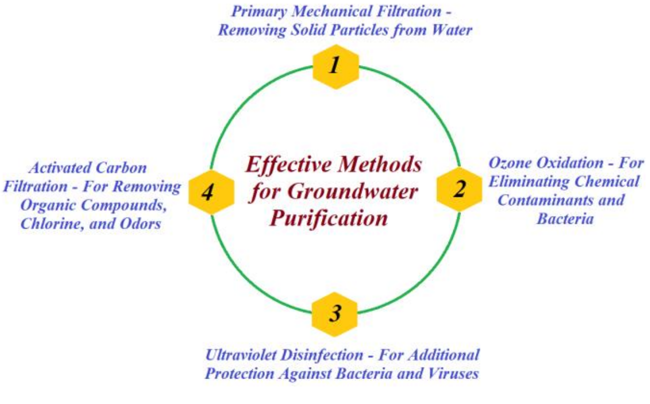

**Figure 1:** Effective Methods for Groundwater Purification

This combination comprehensively improves water quality and ensures a level of purification that meets the necessary requirements.

### 2.1 Research Objects and Methods

The scientific research work presents the results of studying and developing technological processes for the additional purification and disinfection of groundwater to create an autonomous drinking water supply system for a small rural area with 2,000 residents located near the city of Talgar. Significant reserves of groundwater have been identified in this rural area. The groundwater is of a groundwater nature, with a depth of 80 meters, and the discharge rate during test pumping of one well is 100 liters per second. The groundwater class is calcium bicarbonate, with a mineralization of 265 - 280 mg/l, neutral pH (6.5 - 7.3), and medium hardness (3.55 - 4.07 mg-eq/l). The chemical and bacteriological parameters were determined in accredited laboratories for consumer

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rights protection and human well-being supervision in the Almaty region. The obtained results showed that these waters could not be used in household drinking water systems without preliminary purification and disinfection, as they contain high levels of iron, manganese ions, and coliform bacteria (Table 2).

**Table 2:** Chemical and Bacteriological Parameters of Water from Exploration-Operational Well

| Indicators | Quantity | SanPiN 2.1.4.1074-01 |
|---|---|---|
| Hydrogen index (pH), units | 8,8 | 6,5 – 8,5 |
| Total hardness, mmol/L | 3,78 – 4,02 | 7,0 |
| Oxidizability ($KMnO_4$), mg $O_2$/L | 1,28 – 1,76 | 5,0 |
| Nitrates ($NO_3^-$), mg/L | 30,13 | 45,0 |
| Sulfates ($SO_4^{2-}$), mg/L | 46,1 - 47,3 | 500 |
| Chlorides ($Cl^-$), mg/L | 30,5 | 350 |
| Fluorides ($F^-$), mg/L | 0,19 – 0,13 | 1,5 |
| Potassium (K), mg/L | - | - |
| Zinc (Zn, total), mg/L | 0,024 – 0,040 | 5,0 |
| Iron (Fe, total), mg/L | 1,25 | 0,3 |
| Manganese (Mn, total), mg/L | 0,25 | 0,1 |
| Copper (Cu, total), mg/L | 0,01 | 1,0 |
| Lead (Pb, total), mg/L | 0,003 – 0,006 | 0,03 |
| Arsenic (As, total), mg/L | 0,004 | 0,05 |
| Beryllium ($Be^{2+}$), mg/L | - | - |
| Boron (B, total), mg/L | 0,05 | 0,5 |
| Mercury (Hg, total), mg/L | $2{\cdot}10^{-5}$ | 0,0005 |
| Cadmium (Cd, total), mg/L | $5{\cdot}10^{-5}$ | 0,001 |
| Selenium (Se, total), mg/L | 0,002 | 0,01 |
| Strontium ($Sr^{2+}$), mg/L | - | - |
| Dry residue, mg/L | 230 – 1100 | 1500,0 |
| Coli index | 1575 | no more than 3 |
| Total microbial number | 17 | no more than 100 |

To develop the technology for the additional purification and disinfection of well water, a two-stage water treatment scheme, "oxidation-filtration," using ozone as an oxidizer was adopted (Figure 2).

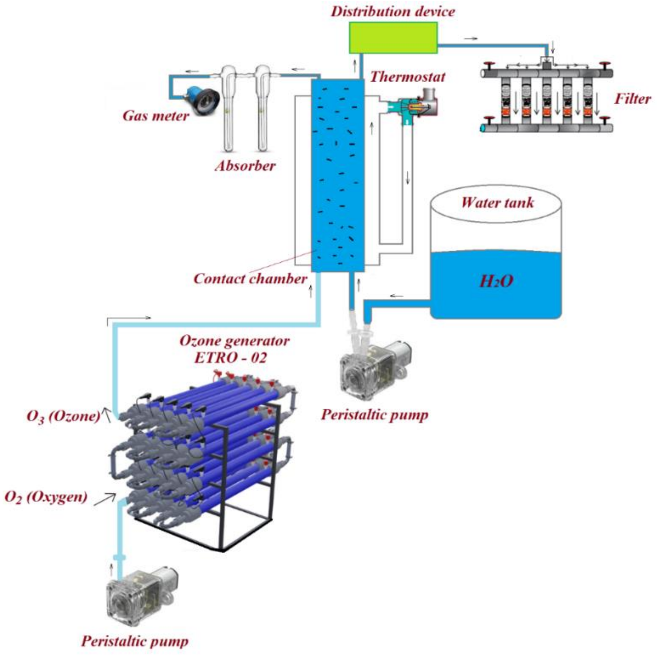

**Figure 2:** Laboratory Setup for Additional Purification and Disinfection of Groundwater

For conducting these laboratory experiments, the ETRO-02 pilot ozonator unit based on electric corona discharge was used (Abdykadyrov et al., 2021; Abdykadyrov et al., 2020). Ozone concentration was introduced in the range of 0.1 – 1.0 mg/min. The ozonizing contact chamber was a quartz glass column with a diameter of 30 mm and a height of 1500 mm. The filter was made of a glass tube with a diameter of 30 mm and a height of 1000 mm. As filtering materials, quartz sand (0.8 – 2.0 mm), activated carbon (1 – 3 mm), powdered anthracite (0.8 – 2.0 mm), as well as a two-layer load consisting of quartz sand and activated carbon were used. In the contact chamber, water supplied by a peristaltic pump was treated with an ozone-air mixture from the ozone generator, resulting in the processes of water disinfection and oxidation of iron and manganese, forming poorly soluble compounds $Fe(OH)_3$ and $MnO_2$. During this process, the color index of the ozonated water increases. The resulting heterogeneous system is directed to filters with the appropriate filtering load. In the filters, the heterogeneous system is separated, resulting in a decrease in the concentrations of iron and manganese due to the adsorption of their poorly soluble compounds, and the ozonated water becomes clearer. This setup allows for the adjustment of ozone dose, the residence time of the treated water in the contact chamber, water temperature, and the filtration rate through the filtering load (Draginsky, 2007). The use of multiple filters in the setup ensures the selection of the nature of the filtering material. The flow rate of the ozone-air mixture was monitored using a gas meter, and the ozone concentration in the ozone-air mixture and the residual ozone concentration were determined by the iodometric method. The required ozone dose for water disinfection and oxidation of contaminants was calculated using the following formula (D).

$$D = \frac{A \cdot t}{V}, \text{mg/l} \qquad (1)$$

Here, (A) is the productivity of the ozone generator (mg/min); (t) is the ozonation time (min); (V) is the volume of the treated water (l). The amounts of iron and manganese ions in the studied water, as well as the water's color, were determined by the photo-colorimetric method (Fernandes et al., 2020). The bacteriological parameters of the studied water samples were determined in the accredited laboratory of GKP "Astana Su Arnasy".

In such a scheme, the first stage involves the oxidation and coagulation of contaminants, while the second stage involves the separation of the resulting heterogeneous system and the disinfection of the water (Fernandes et al., 2020; Adarsh et al., 2013). The advantages of ozone compared to other oxidizers are shown in Figure 3 (Draginsky, 2007; Abdykadyrov et al., 2024).

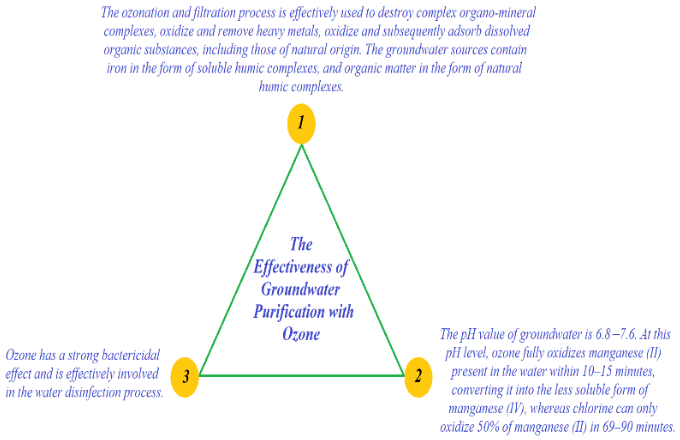

**Figure 3:** The Effectiveness of Groundwater Purification with Ozone

During the process, the use of ozone as an oxidizer has shown that it significantly simplifies the technological scheme of water purification. It promotes deep disinfection and the removal of iron and manganese without deteriorating the taste properties of the water (Abdykadyrov et al., 2023; Ngwenya et al., 2012; Kalandarov, 2024). Such technological units increase the efficiency of preparing both surface and groundwater for drinking purposes. However, implementing such water purification schemes requires precise tuning of the technological process, particularly the optimal conditions for ozonation. This includes determining the necessary amount of ozone for oxidizing organic and mineral contaminants and disinfecting the water, the contact time between the ozone-air mixture and the treated water, and the impact of the chemical nature and concentration of contaminants on the purification degree. In some cases, exceeding the ozone dose can lead to the formation of toxic reaction products in the treated water (Draginsky, 2007). The optimization of the technological process parameters for additional purification and disinfection of water from the exploration and operational well was carried out in an extended laboratory setup. This setup consisted of a reservoir, a peristaltic pump, an ozone generator, a contact chamber, an absorber, a gas meter, a thermostat, a distribution device, and a filter (Figure 2).

### 2.2 Theory Of Ozone Treatment Of Groundwater

Mathematical models and equations describing the process of ozone treatment of groundwater include the interaction of ozone with contaminants in the water, the decomposition of ozone, and the contact time (Draginsky, 2007; Derco et al., 2021). The main mathematical equations governing the process are as follows:

1. *Ozone Generation:* The production of ozone in an ozone generator is primarily described by the following equation (Jodzis and Baran, 2022):

$$O_2 \xrightarrow{\text{Electrical discharges}} O_3 \qquad (2)$$

*2. Ozone Decomposition Kinetics:* The kinetics of ozone decomposition in water is described by the following differential equation ( Lovato et al., 2009):

$$\frac{d[O_3]}{dt} = -k_d[O_3] \qquad (3)$$

where $[O_3]$ is the ozone concentration at time (t), and ($k_d$) is the decomposition constant of ozone.

3. *Reaction of Ozone with Contaminants:* The reaction of ozone with contaminants in water can be described by the following equation (Von Sonntag and Von Gunten, 2012):

$$O_3 + R \rightarrow P \qquad (4)$$

where (R) is the contaminant, and (P) are the reaction products.

The kinetics of this reaction (Draginsky, 2007; Von Sonntag and Von Gunten, 2012):

$$\frac{d[R]}{dt} = -k_r[O_3]\,[R] \qquad (5)$$

where ($k_r$) is the reaction rate constant.

4. *Time-Dependence of Ozone Concentration:* The time - dependence of ozone concentration can be described as follows (Von Sonntag, and Von Gunten, 2012):

$$[O_3](t) = [O_3]_o e^{-k_d t} \qquad (6)$$

where $[O_3]_o$ is the initial ozone concentration.

5. *Time-Dependence of Contaminant Concentration:* The time - dependence of the contaminant concentration can be described by the following expression:

$$[R](t) = [R]_o e^{-k_r [O_3]_o t} \qquad (7)$$

where [R]o is the initial concentration of the contaminant.

6. *Overall Ozone Balance Equation:* The equation describing the overall ozone balance is as follows:

$$\frac{d[O_3]}{dt} = -k_d[O_3] - k_r[O_3][R] \qquad (8)$$

*Reaction Time Calculation:* The time for the complete reaction of ozone with a specific contaminant in water is determined by the following equation (Draginsky, 2007):

$$t = \frac{1}{k_r[O_3]_o}\ln\left(\frac{[R]_o}{[R](t)}\right) \qquad (9)$$

These equations (2,3,4...9) describe the generation of ozone, its decomposition in water, and its reactions with contaminants. By using these equations, the ozone treatment process can be mathematically modeled and effectively managed. Based on this theoretical foundation, we have decided to conduct experimental work for scientific research in collaboration with the Kazakh National Research Technical University named after K.I. Satbayev (Republic of Kazakhstan) and the "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University (Republic of Uzbekistan).

## 3. RESULTS AND DISCUSSIONS

Groundwater pollution and its purification are among the most pressing contemporary issues. Considering these issues, a joint scientific research project was conducted by the Kazakh National Research Technical University named after K.I. Satbayev (Republic of Kazakhstan) and the "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University (Republic of Uzbekistan). This research aimed to determine how to effectively detoxify harmful compounds in groundwater using a pilot autonomous unit. The pilot unit employs various methods, including mechanical filtration, ozone oxidation, ultraviolet disinfection, and activated carbon filtration.

### 3.1 Research Results

Comprehensive studies were conducted in the laboratory setup to determine the effects of ozone dose, contact time of the treated water with the ozone-air mixture, water temperature, contaminant concentrations, filtration rate, iron, manganese, and the degree of water disinfection in accordance with the sanitary rules and regulations 2.1.4.1074-01. The ozone dose was varied between 1.5 ÷ 3.5 mg/l, the contact time with the ozone-air mixture between 5 ÷ 20 minutes, the water temperature between 9 ÷ 15ºC, the filtration rate between 8 ÷ 15 m/hour, iron concentration between 0.75 ÷ 1.25 mg/l, and manganese concentration between 0.10 ÷ 0.25 mg/l. As a result of the studies, the optimal parameters for the processes of iron and manganese removal, precipitation, and disinfection of groundwater were determined: ozone dose of 1.5 mg/l, contact time with the ozone-air mixture of 20 minutes, filtration rate of 15 m/hour, and residual ozone concentration of 0.1 ÷ 0.3 mg/l. The quality indicators of the water treated in the laboratory setup (Table 3) demonstrate that it can be used in an autonomous drinking water supply system. The levels of iron, manganese, and coliform index comply with the requirements of the sanitary rules and regulations 2.1.4.1074-01.

**Table 3:** Quality Indicators of Raw and Prepared Drinking Water According to the "Oxidation-Filtration" Scheme

| Indicators | Source Water | Water after Treatment |
|---|---|---|
| Hydrogen Index (pH), units | 8,8 | 6,8 |
| Iron Content (total), mg/l | 1,25 | 0,1 |
| Manganese Content, mg/l | 0,25 | 0,03 |
| Coli Index | 1575 | n/d |
| Total Microbial Count | 17 | n/d |

Based on the research work, the purification of water from the well to remove heavy metals and disinfect harmful bacteria was carried out using the ETRO-02 ozonator unit based on pilot electric corona discharge (Abdykadyrov, 2014). The main technological scheme of water purification includes the following stages (Figure 4).

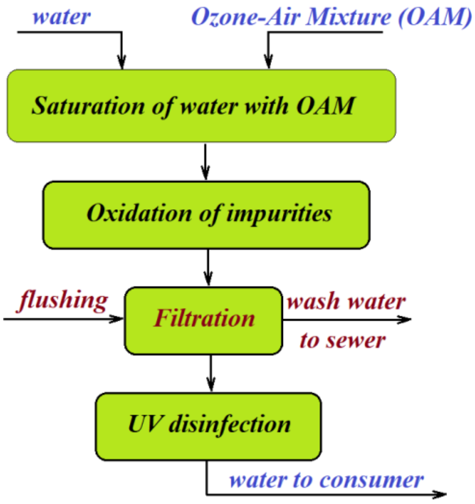

**Figure 4:** The principal scheme of artesian water treatment

In the first stage, the initial water is saturated with the ozone-air mixture, and then the oxidation and disinfection process occurs in the contact apparatus. In the second stage, suspended particles are removed by filtering the water through quartz sand, and the adsorption of organic

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contaminants on the surface of activated carbon takes place. In the third stage, the purified and disinfected water undergoes additional treatment with ultraviolet rays before being supplied to the consumer. A filter cleaning stage is also included, and the resulting dirty water is discharged into the sewer. This scheme allows for the purification and disinfection of water containing excess iron, manganese, and organic substances. The main diagram of the technological unit for purifying groundwater with a capacity of 5 $m^3/h$ is shown in Figure 5.

The initial water from the well is supplied to the contact chamber via a centrifugal pump, an ozone-air mixture (ETRO-02 ozone generator), and an ejector, where the oxidation of iron, manganese, and organic substances present in the water and its disinfection occur. Unreacted ozone is directed to the degasser and eliminated. The unit includes a control unit that allows the production of different amounts of ozone. To increase the mixing coefficient of water and the ozone-air mixture, the technological scheme employs an ejector mixing system. Due to its kinetic energy, water in the ejector captures the mass of the ozone-air mixture and converts it into a water-air emulsion. The use of the ejector allows significantly reducing the volume of the contact chamber and achieving an ozone absorption coefficient of up to 90%, with the height of the contact chamber not exceeding 2.0 m. From the contact chamber, the ozonated water is fed into the first chamber of the pressure filter filled with quartz sand, where large dispersed contaminants are removed. In the second contact chamber filled with activated carbon, the adsorption of unoxidized organic substances occurs. After passing through the activated carbon layer, the water undergoes bactericidal treatment to prevent secondary bacterial contamination. Then, the purified and disinfected water is directed to the storage reservoir, from which it is supplied to the consumer by a centrifugal pump.

Comprehensive studies conducted on an enlarged laboratory setup for preparing groundwater from wells allow the creation of an autonomous drinking water system. This made it possible to determine the main technological parameters for the processes of iron removal, demanganization, clarification, and disinfection. The conducted scientific research enabled the development of a technological unit with a capacity of 5 $m^3/h$ for water treatment technology.

When choosing the unit, it was considered that, with the iron content in the water varying up to 1.25 mg/l and the manganese content up to 0.25 mg/l, the technological process could be purposefully adjusted and the energy costs for ozone production could be reduced without reducing the efficiency of the purification and disinfection processes. A technical specification for the design of an industrial unit was developed, and its implementation will address the socially important issue of creating autonomous drinking water supply systems.

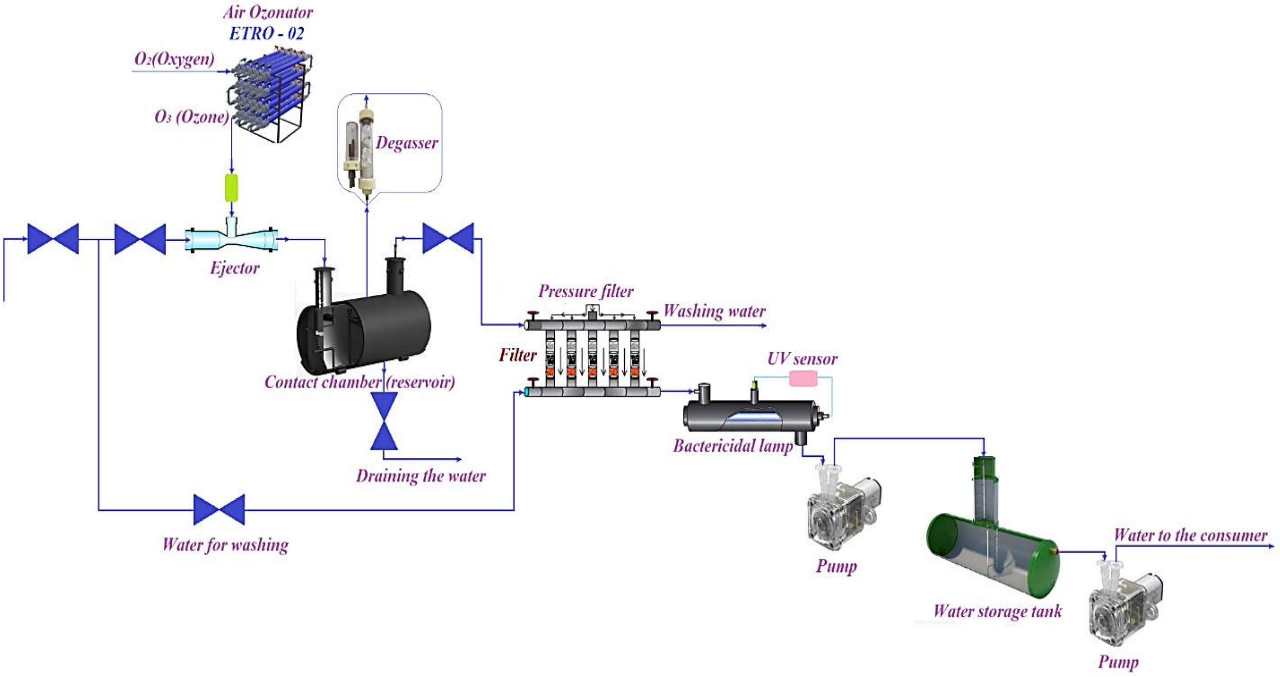


**Figure 5:** Technological Scheme of the Artesian Water Purification Unit Used to Create an Autonomous Drinking Water Supply System

*Below is a brief explanation of each step:*

- Air Ozonator (ETRO-02): This device converts oxygen in the air into ozone;
- Ejector: Introduces ozone into the water flow to create an ozonated water solution;
- Contact Chamber (Reservoir): Ozone is introduced into the water in this chamber for disinfection;
- Degasser: Removes excess gases by separating ozone from the water;
- Pressure Filter: Uses a pressure filter to filter the water;
- Bactericidal Lamp: Uses ultraviolet radiation to eliminate bacteria;
- Water Storage Tank: Stores the purified water before it is delivered to the consumer.

This technological scheme involves several integrated purification and disinfection stages to ensure efficient water purification and safe drinking water provision.

## 3.2 Mathematical Modeling of Research Results

In the scientific research work, mathematical modeling was conducted in two scenarios to improve the efficiency of the technological process:

*Option 1: Oxidation Process of Excess Heavy Metals.*

The oxidation reactions of iron (Fe) and manganese (Mn) with ozone ($O_3$) found in water extracted from the well proceed as follows. *Oxidation of Iron with Ozone:* When iron (II) ion ($Fe^{2+}$) reacts with ozone, iron (III) ion ($Fe^{3+}$) is formed:

$$2Fe^{2+} + O_3 + 2H_2O \rightarrow 2Fe^{3+} + O_2 + 4OH^-$$

$$Fe^{3+} + 3OH^- = Fe(OH)_3 \downarrow \qquad (10)$$

$$Fe(OH)_2 \downarrow + O_3 + H_2O = Fe(OH)_3 \downarrow + O_2 + OH^-$$

*Oxidation of Manganese with Ozone:* When manganese (II) ion ($Mn^{2+}$) reacts with ozone, manganese (IV) dioxide ($MnO_2$) is formed:

$$2Mn^{2+} + O_3 + 4H_2O \rightarrow 2MnO_2 + O_2 + 8H^+$$

$$6Mn^{2+} + O_3 + 12OH^- = 3Mn_2O_3(H_2O) \downarrow + 3H_2O \qquad (11)$$

$$Mn(OH)_2 + O_3 = MnO_2 \downarrow + O_2 + H_2O$$

These reactions oxidize the iron and manganese ions in the water, converting them into insoluble compounds, thereby allowing their removal from the water (the research results are shown in Tables 4 and 5).

**Table 4:** Effect of Ozone Amount on Heavy Metal Concentration

| № | Heavy metals | Ozone amount ($O_3$), mg/L (oxidation time t = 20 minutes) | | | | |
|---|---|---|---|---|---|---|
| | | $O_3$ = 0 mg/L | $O_3$ = 0,5 mg/L | $O_3$ = 0,75 mg/L | $O_3$ = 1 mg/L | $O_3$ = 1,5 mg/L |
| 1 | Iron ($Fe^{2+}$) | 1,25 | 0,87 | 0,54 | 0,35 | 0,1 |
| 2 | Manganese ($Mn^{2+}$) | 0,25 | 0,18 | 0,075 | 0,05 | 0,03 |

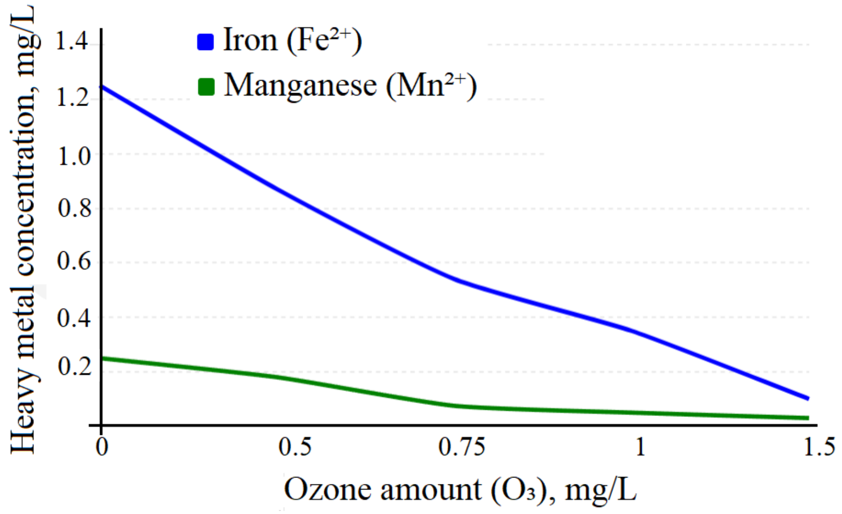


**Figure 6:** Ozone Treatment Impact on Heavy Metal Concentration

This graph shows the decrease in the concentration of iron ($Fe^{2+}$) and manganese ($Mn^{2+}$) with the increase in the amount of ozone ($O_3$). The concentration of iron significantly decreases as the amount of ozone increases from 0 to 1.5 mg/L, dropping from an initial value of 1.4 mg/L to approximately 0.1 mg/L. The concentration of manganese also decreases, but at a slower rate, from an initial value of 0.2 mg/L to approximately 0.03 mg/L. This indicates that ozone effectively oxidizes both iron and manganese, reducing their concentrations.

**Table 5:** Effect of Oxidation Time on Heavy Metal Concentration with Ozone Amount of 1.5 mg/L

| № | Heavy metals | Oxidation time (ozone amount $O_3$ = 1,5 mg/L) | | | | |
|---|---|---|---|---|---|---|
| | | t = 0 minutes | t = 5 minutes | t = 10 minutes | t = 15 minutes | t = 20 minutes |
| 1 | Iron ($Fe^{2+}$) | 1,25 | 0,77 | 0,65 | 0,42 | 0,1 |
| 2 | Manganese ($Mn^{2+}$) | 0,25 | 0,15 | 0,068 | 0,047 | 0,03 |

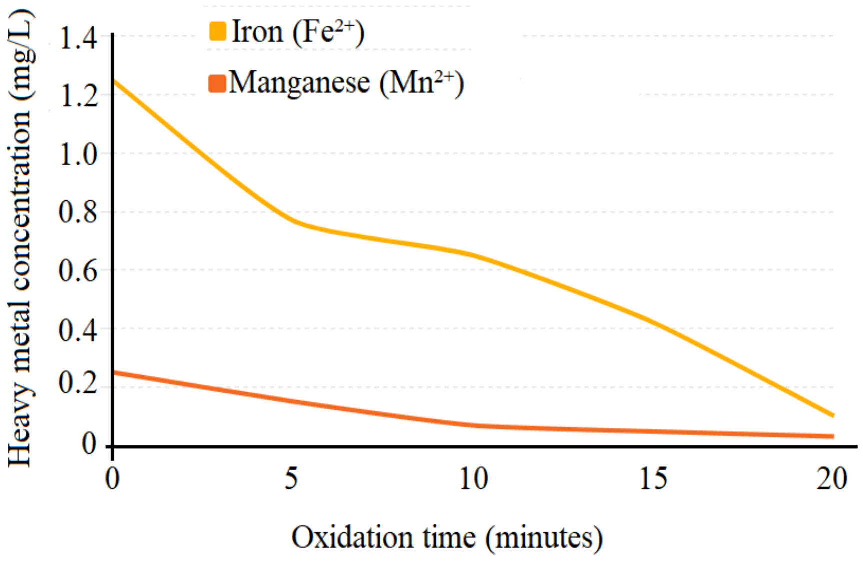
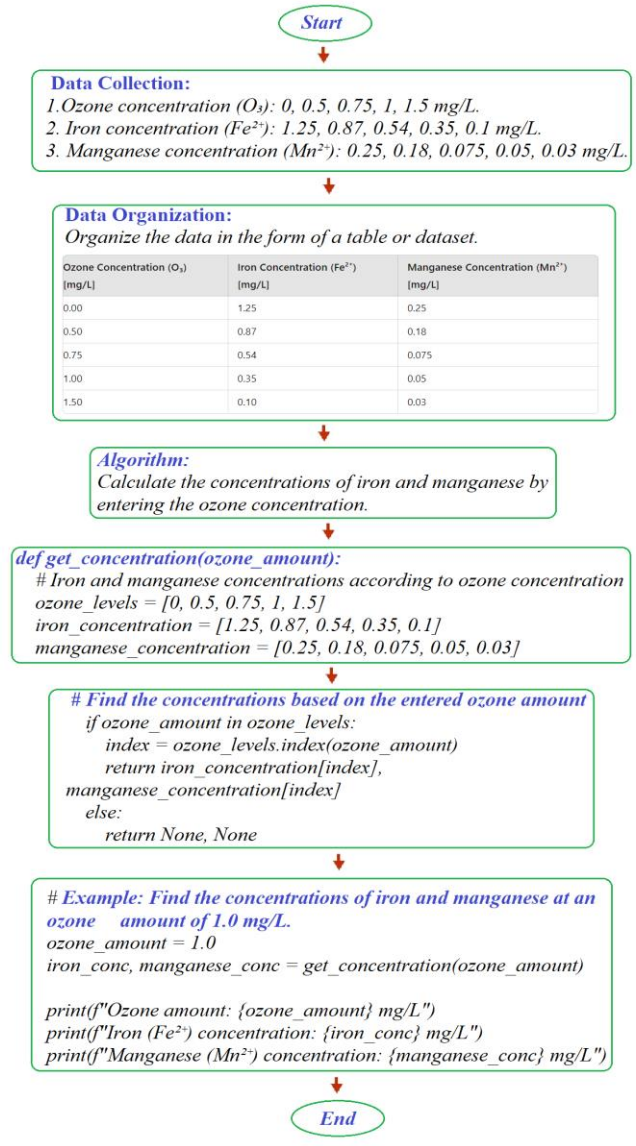


**Figure 7:** Effect of Oxidation Time on Heavy Metal Concentration with Ozone Treatment

This graph shows the effect of oxidation time (minutes) on the concentration of heavy metals (iron ($Fe^{2+}$) and manganese ($Mn^{2+}$)). The concentration of iron significantly decreases as the oxidation time increases, dropping from an initial value of approximately 1.4 mg/L to about 0.1 mg/L within 20 minutes. The concentration of manganese also decreases, but at a slower rate, from an initial value of 0.2 mg/L to approximately 0.03 mg/L within 20 minutes. This indicates that using ozone over an extended period can effectively remove heavy metals from the water.

Based on the data obtained from this experiment, the algorithmic code for the process of oxidizing water to remove heavy metals can be written in Python. To enhance the accuracy of the numerical spectral correlation, the analytical signal can be reconstructed for processing the incomplete spectrum of the signal (Smailov et al., 2023; Sabibolda et al., 2022). The following steps can be taken to create the algorithm (Figure 8):



**Data Collection:**
1. Ozone concentration ($O_3$): 0, 0.5, 0.75, 1, 1.5 mg/L.
2. Iron concentration ($Fe^{2+}$): 1.25, 0.87, 0.54, 0.35, 0.1 mg/L.
3. Manganese concentration ($Mn^{2+}$): 0.25, 0.18, 0.075, 0.05, 0.03 mg/L.

**Data Organization:**
Organize the data in the form of a table or dataset.

| Ozone Concentration ($O_3$) [mg/L] | Iron Concentration ($Fe^{2+}$) [mg/L] | Manganese Concentration ($Mn^{2+}$) [mg/L] |
|---|---|---|
| 0.00 | 1.25 | 0.25 |
| 0.50 | 0.87 | 0.18 |
| 0.75 | 0.54 | 0.075 |
| 1.00 | 0.35 | 0.05 |
| 1.50 | 0.10 | 0.03 |

**Algorithm:**
Calculate the concentrations of iron and manganese by entering the ozone concentration.

```
def get_concentration(ozone_amount):
    # Iron and manganese concentrations according to ozone concentration
    ozone_levels = [0, 0.5, 0.75, 1, 1.5]
    iron_concentration = [1.25, 0.87, 0.54, 0.35, 0.1]
    manganese_concentration = [0.25, 0.18, 0.075, 0.05, 0.03]
```

```
    # Find the concentrations based on the entered ozone amount
      if ozone_amount in ozone_levels:
         index = ozone_levels.index(ozone_amount)
         return iron_concentration[index],
manganese_concentration[index]
      else:
         return None, None
```

```
# Example: Find the concentrations of iron and manganese at an
ozone    amount of 1.0 mg/L.
ozone_amount = 1.0
iron_conc, manganese_conc = get_concentration(ozone_amount)

print(f"Ozone amount: {ozone_amount} mg/L")
print(f"Iron (Fe²⁺) concentration: {iron_conc} mg/L")
print(f"Manganese (Mn²⁺) concentration: {manganese_conc} mg/L")
```

**Figure 8:** Algorithm for Determining Heavy Metal Concentrations Based on Ozone Amount

The algorithm illustrated in Figure 8 allows for the calculation of iron and manganese concentrations based on the amount of ozone. Similarly, it demonstrates the algorithm for determining the concentrations of iron ($Fe^{2+}$) and manganese ($Mn^{2+}$) based on the amount of ozone ($O_3$). The first step is data collection, where the amount of ozone and the corresponding concentrations of iron and manganese are provided. In the second step, the data is organized in the form of a table or dataset. Finally, a Python function is presented that calculates the concentrations of iron and manganese according to the input amount of ozone.

*Option 2: Disinfection Process of Harmful Microorganisms in Water.*

The process of disinfecting groundwater with ozone and ultraviolet (UV) radiation is complex, but we first theoretically calculated it and then computed the algorithmic steps in Python. Initially, we determine the total number of microbes and the coliform index, and then we perform calculations for the disinfection process using ozone and UV radiation. The total number of microbes refers to the overall count of microorganisms in the water. The coliform index indicates the number of coliform bacteria (e.g., Escherichia coli) in the water. The process of disinfecting the total number of microbes and the coliform index found in the water extracted from the well using ozone ($O_3$) and then UV radiation proceeds as follows:

*Ozone Disinfection Process:* The efficiency of ozone in destroying bacteria depends on its concentration and the contact time. To kill microbes, the product of ozone concentration (C) and contact time (T) must equal a specific value (CT). This value varies for different microbes. For example, in our case, the CT value for E. coli is 30 mg·min/L. If the ozone concentration in the water is 1.5 mg/L and the contact time is 20 minutes:

$$CT = C \cdot T = 1{,}5\ \text{mg/L} \cdot 20\ \text{minutes} = 30\ \text{mg·min/L} \tag{12}$$

This value of 30 mg·min/L from equation (12) is sufficient for E. coli.

*UV Radiation Disinfection:* The effectiveness of UV radiation in killing bacteria depends on the radiation dose, measured in microjoules per square centimeter (μJ/cm²). The required dose for disinfecting water varies depending on the type of microorganism. For example, in our case, the required dose for E. coli is between 30,000 and 40,000 μJ/cm². If, for instance, the UV lamp has a power of 40 W, the water flow rate is 1 L/sec, and the exposure time is 10 seconds, the dose can be calculated as follows:

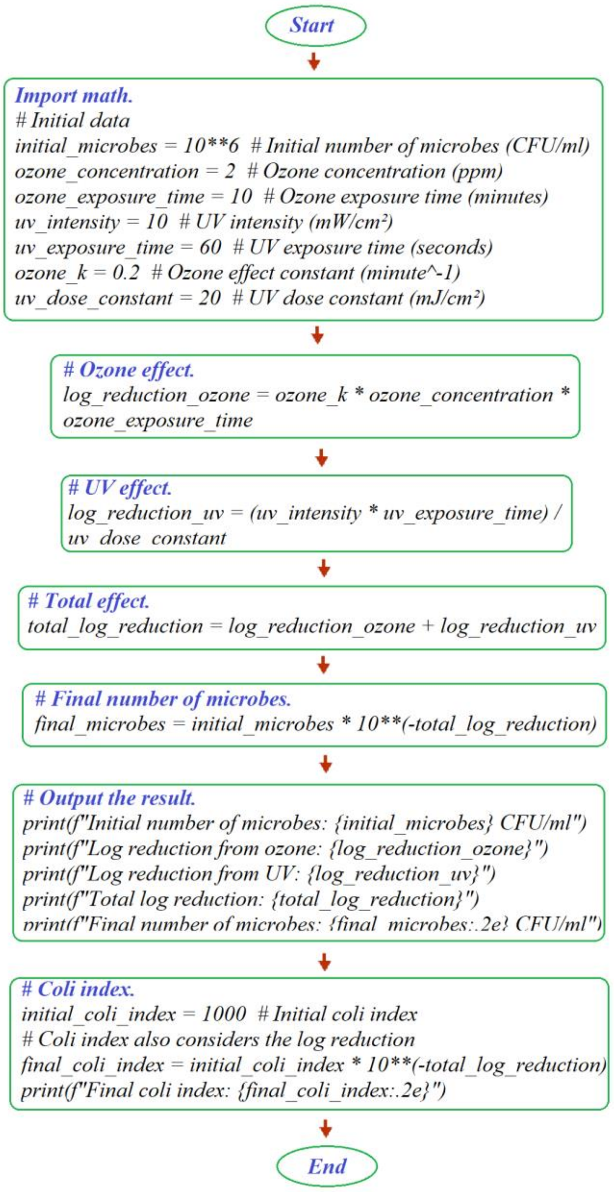
$$\text{Dose} = \frac{\text{Power}}{\text{Water Flow Rate}} \cdot \text{Exposure Time} = \frac{40W}{1\ L/s} \cdot 10s = 400\ \text{W} \cdot \text{s/L} \tag{13}$$

To convert the radiation dose to microjoules per square centimeter (1 W = 10^6 μJ):

$$400\ \text{W} \cdot \frac{\text{s}}{\text{L}} = 400 \cdot 10^6 \frac{\mu\text{J}}{\text{L}} = 400{,}000 \mu\text{J}/cm^2 \tag{14}$$

This dose calculated in equations (13) and (14) is sufficient to kill E. coli.

To perform theoretical calculations for the combined disinfection process of the total number of microbes and the coliform index using ozone and ultraviolet (UV) radiation, the following algorithmic steps were executed in Python (Figure 9):



```
Import math.
# Initial data
initial_microbes = 10**6  # Initial number of microbes (CFU/ml)
ozone_concentration = 2  # Ozone concentration (ppm)
ozone_exposure_time = 10  # Ozone exposure time (minutes)
uv_intensity = 10  # UV intensity (mW/cm²)
uv_exposure_time = 60  # UV exposure time (seconds)
ozone_k = 0.2  # Ozone effect constant (minute^-1)
uv_dose_constant = 20  # UV dose constant (mJ/cm²)
```

```
# Ozone effect.
log_reduction_ozone = ozone_k * ozone_concentration *
ozone_exposure_time
```

```
# UV effect.
log_reduction_uv = (uv_intensity * uv_exposure_time) /
uv_dose_constant
```

```
# Total effect.
total_log_reduction = log_reduction_ozone + log_reduction_uv
```

```
# Final number of microbes.
final_microbes = initial_microbes * 10**(-total_log_reduction)
```

```
# Output the result.
print(f"Initial number of microbes: {initial_microbes} CFU/ml")
print(f"Log reduction from ozone: {log_reduction_ozone}")
print(f"Log reduction from UV: {log_reduction_uv}")
print(f"Total log reduction: {total_log_reduction}")
print(f"Final number of microbes: {final_microbes:.2e} CFU/ml")
```

```
# Coli index.
initial_coli_index = 1000  # Initial coli index
# Coli index also considers the log reduction
final_coli_index = initial_coli_index * 10**(-total_log_reduction)
print(f"Final coli index: {final_coli_index:.2e}")
```

**Figure 9:** Python Program Flowchart for Ozone and UV Disinfection Process

Figure 9 illustrates the flowchart of the Python program, which describes the process of calculating the number of microbes and the coliform index under the influence of ozone and ultraviolet (UV) radiation. The diagram begins with the input of initial data (e.g., the number of microbes, ozone concentration, and UV radiation intensity). Next, the logarithmic reduction effects of ozone and UV radiation are calculated separately. These two effects are then combined to determine the overall logarithmic reduction. Finally, the resulting number of microbes and the coliform index are calculated, and the results are displayed on the screen. This diagram visually represents the step-by-step algorithm of the program.

### 3.3 Discussion of Scientific Research Work

In the research work, it was observed that when the amount of ozone is 1.5 mg/L, the initial concentration of heavy iron ions in the water decreases from 1.25 mg/L to 0.1 mg/L, and the concentration of manganese decreases from 0.25 mg/L to 0.03 mg/L. These values fully meet the requirements specified in the sanitary rules and regulations 2.1.4.1074-01 (Figures 10 and 11).

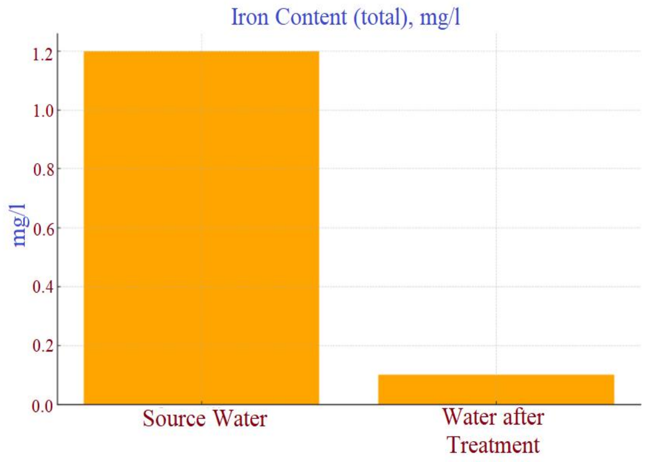


**Figure 10:** Changes in Iron Ions Before and After Ozonation (Ozone concentration 1.5 mg/L)

Figure 10 shows the iron content in water, measured in milligrams per liter (mg/L), before and after treatment. The initial amount of iron in the water is approximately 1.2 mg/L. After treatment, the iron content significantly decreases to about 0.1 mg/L. This indicates that the purification process is highly effective in reducing the iron content in the water. The iron content decreases by approximately 90%, demonstrating the efficiency of the water purification process.

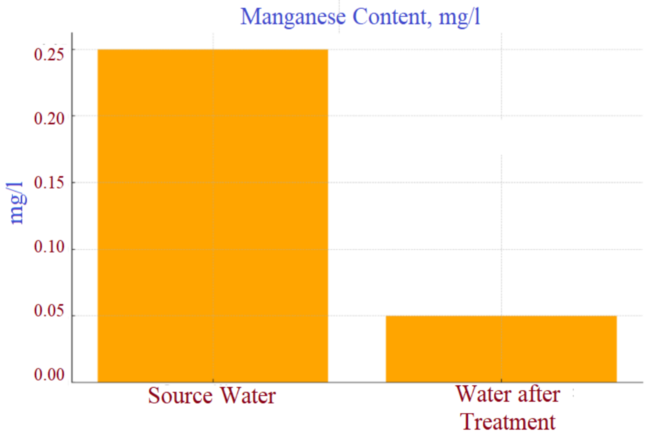


**Figure 11:** Changes in Manganese Compounds Before and After Ozonation (Ozone concentration 1.5 mg/L)

Figure 11 shows a bar chart comparing the manganese content (mg/L) levels in the initial water and the treated water. For example, the manganese content in the initial water is approximately 0.25 mg/L, while after treatment, the manganese content decreases to about 0.05 mg/L.

During the ozonation process, the pH property plays an important role. First, the pH level determines the solubility and stability of ozone in water, which is necessary to enhance the effect of ozone. Second, at lower pH values, the decomposition of ozone occurs more rapidly, resulting in the formation of hydroxyl radicals, which clean the water more effectively. Third, the pH level affects the efficiency of the ozonation process and the quality of the treated water. Fourth, monitoring pH levels is important to optimize the disinfecting effect of ozone and to prevent system corrosion (Figure 12).

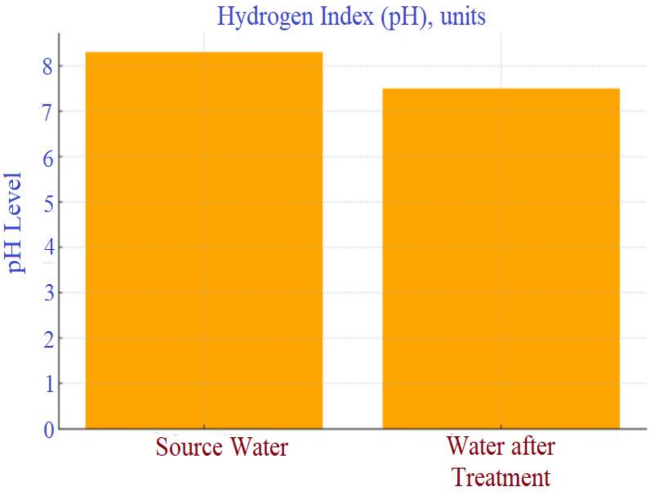


**Figure 12:** Comparative diagram of the hydrogen index (pH) of water before and after purification

Figure 12 shows a bar chart comparing the hydrogen index (pH) of initial water and water after purification. For example, the pH level of the initial water is approximately 8 units. After purification, the pH level of the water is approximately pH = 7.5 units. The diagram shows that the pH level of the water slightly decreases after the purification process. The initial water's pH level is alkaline, at pH = 8, while after purification, it is slightly neutralized to pH = 7.5.

The presence of microorganisms in water, such as the coliform index and the total microbial count, poses significant health risks. These indicators show the level of bacterial contamination in the water, which can cause intestinal infections and other diseases. The coliform index is often an indicator of fecal contamination, and its high level suggests poor sanitary conditions of the water sources. A high total microbial count can be dangerous for individuals with weakened immune systems, as it indicates the abundance of pathogenic bacteria.

Ozone water purification effectively reduces the harmful coliform index and total microbial count, as ozone possesses strong disinfectant properties. It disrupts the cell walls of bacteria, halting their reproduction and completely destroying them. Additionally, ozone is an environmentally friendly method, as it leaves no chemical residues in the water and quickly breaks down into oxygen. The research results are shown in Figures 13 and 14 below.

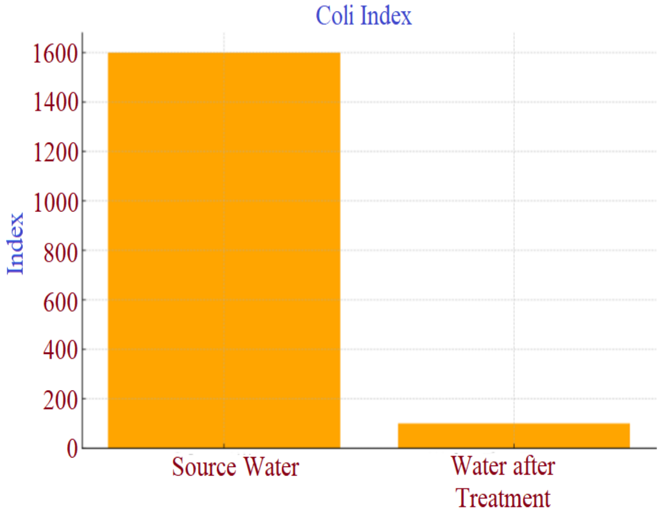


**Figure 13:** Change in Coliform Index Before and After Ozonation

Figure 13 shows a bar chart comparing the coliform index of initial water and water after purification. For example, the coliform index in the initial water is approximately 1600 units. After purification, the coliform index in the water is approximately 100 units. The diagram shows a significant decrease in the coliform index as a result of the purification process, indicating a substantial reduction in the level of bacterial contamination in the water.

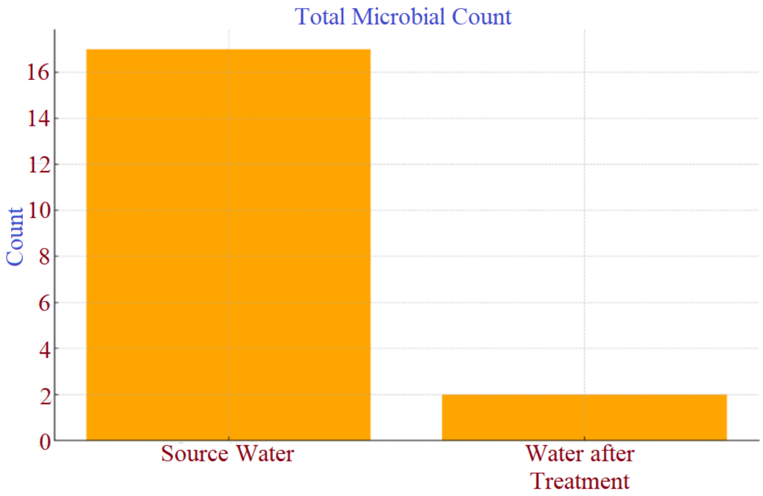


**Figure 14:** Change in Total Microbial Count Before and After Ozonation

Figure 14 shows a bar chart comparing the total microbial count of initial water and water after purification. For example, the total microbial count in the initial water is approximately 16 units. After purification, the total microbial count in the water is approximately 2 units. The diagram shows a significant reduction in microbial contamination after the purification process. This demonstrates the effectiveness of the purification method and the improvement in water quality.

However, to completely purify and disinfect the water, it was necessary to add comprehensive purification methods to the technological scheme (Figure 5). Figure 5 shows the use of UV radiation and filters made from various sorbents along with ozone. The results of the study can be observed in Table 6 below.

**Table 6:** Results of Comprehensive Water Purification Methods

| Indicators | Groundwater extracted from the initial well | Water fully purified using integrated methods | SanPiN 2.1.4.1074-01 |
|---|---|---|---|
| Hydrogen Index (pH), units | 8,8 | 6,8 | 6,5 – 8,5 |
| Iron Content (total), mg/l | 1,25 | 0,1 | 0,3 |
| Manganese Content, mg/l | 0,25 | 0,03 | 0,1 |
| Coli Index | 1575 | n/d | no more than 3 |
| Total Microbial Count | 17 | n/d | no more than 100 |

Table 6 compares the quality of groundwater from the initial well and water purified using comprehensive methods against sanitary rules and norm standards. The levels of iron and manganese in the initial water are high, but after purification, these levels meet the requirements of sanitary rules and norm standards. Additionally, while the coliform index and microbial count in the initial water are high, these indicators are undetectable in the purified water, indicating complete purification. Overall, the comprehensive purification methods significantly improve the water quality, making it compliant with sanitary standards.

## 4. CONCLUSION

This study focuses on the decontamination and purification of harmful substances in the groundwater of the Talgar district in the Almaty region using a pilot autonomous installation. The research results show that the groundwater in the area contains high levels of heavy metals (iron ($Fe^{2+}$) and manganese ($Mn^{2+}$)), chemical compounds, and microorganisms (coliform index and total microbial count), which are harmful to human health and the environment. To eliminate these harmful substances, comprehensive purification methods were used, including the pilot ETRO-02 ozonator installation based on electric discharge, filtration methods, and ultraviolet (UV) radiation.

In the study, the concentration of iron significantly decreases with increased oxidation time, from an initial value of approximately 1.4 mg/L to about 0.1 mg/L within 20 minutes. The concentration of manganese also decreases, albeit at a slower rate, from an initial value of 0.2 mg/L to about 0.03 mg/L within 20 minutes. This demonstrates the effectiveness of using ozone to remove heavy metals from water over a prolonged period. Similarly, the initial water had a total microbial count of 17 and a coliform index of 1575, which were completely eliminated after passing through the purification system. These values comply with sanitary rules and standards (SanPiN 2.1.4.1074-01). Additionally, the data obtained from the experiments were processed using SMath Solver and Python, with their algorithmic code written.

The quality indicators of the water processed in the laboratory installation prove that it can be used in an autonomous drinking water supply system. This research is an important step towards providing clean and safe drinking water in rural and urban areas. The results of the practical work demonstrate that comprehensive purification methods significantly improve the quality of groundwater, allowing its use in safe drinking water systems.

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