JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(9), 43–56
https://doi.org/10.12911/22998993/221253
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.04.16
Accepted: 2026.07.15
Published: 2026.08.01

Research and optimization of the electroflotation process for the purification of wastewater from mechanical engineering production from heavy metals

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ABSTRACT

This paper presents the results of experimental studies on the removal of heavy metals from industrial wastewater using electroflotation. Field observations revealed a consistent excess of maximum permissible concentrations of iron, manganese, zinc, and copper in the wastewater of a mechanical engineering plant, exceeding fishery standards. The main sources of pollution were identified: technological processes of abrasive waterjet cutting of metal, destruction of abrasive material (garnet sand), and elevated background concentrations of metals in tap water. A laboratory electroflotation unit was designed, and experimental studies of wastewater treatment were conducted. The optimal process parameters were determined: current density of 420 A/m², voltage >50 V, and processing time of 20 minutes. The electrochemical aspects of the process, including the phenomena of electrode passivation, polarization, and corrosion, were studied. It was established that the bulk of heavy metals is in an undissolved form, which ensures the effectiveness of flotation extraction without preliminary chemical preparation. The achieved degree of purification ensures compliance with water quality standards.

Keywords: heavy metals, industrial wastewater, electroflotation, water purification, waterjet cutting, electrode passivation, current density.

INTRODUCTION

Heavy metals are among the most hazardous water pollutants. Their main feature is the ability to persist in the environment for indefinite time, as well as their capacity for bioaccumulation and biomagnification (accumulation in organisms and increasing concentration at each level of the trophic chain) [Karacheva, 2022]. Once they enter a water body, metals do not decompose naturally, but are redistributed among water, bottom sediments, and aquatic organisms, creating a long-term threat [Al-Amrani and Onaizi, 2024]. Industrial activities make the primary contribution to pollution. Key sources include the wastewater from machine-building, metalworking, electroplating, mining, and metallurgical enterprises [Chukaeva et al., 2025]. They contain high concentrations of metal ions, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), cadmium (Cd), lead (Pb), and mercury (Hg) [Feisal et al., 2024].

The problem of heavy metal pollution is global. High concentrations of metals are recorded in various regions of the world, including the Ganges River, Bangladesh, the Mediterranean Sea, water bodies in the northern regions of Russia, where ecosystem vulnerability is particularly high, as well as rivers in megacities [Wang et al., 2024]. Of particular concern are the water bodies with slow water exchange, where the period of complete renewal of the water mass can last several decades [Kartamysheva, 2017].

Heavy metals have a direct toxic effect on aquatic organisms, especially fish, which serve as an important link in the food chain and an indicator of the ecosystem's health. Fish absorb the metals from water through their gills and skin, as well as through their diet (contaminated zooplankton, benthos) [Ávila et al., 2025].

One of the key mechanisms of heavy metal toxicity is the induction of oxidative stress. Once inside the body, metal ions stimulate the excessive generation of reactive oxygen species. This leads to damage to cell membranes through the oxidation of lipids, proteins, and DNA, disrupting homeostasis and causing cell death. The toxic effects of metals manifest in reduced growth and survival rates, impaired reproductive function, and behavioral abnormalities [Antoninova et al., 2023].

Traditional methods of treating industrial wastewater from heavy metals (ion exchange, reverse osmosis, chemical precipitation) are often expensive, energy-intensive, or lead to the formation of large quantities of toxic sludge, necessitating the search for new, more efficient, and cost-effective solutions [Singh and Sharma, 2024].

Heavy metal pollution of water bodies is a complex environmental and socio-economic problem that requires stricter control over industrial wastewater discharges, the development and implementation of effective and affordable treatment methods, and continuous monitoring of the state of water bodies. The industrial wastewater from mechanical engineering plants often contains elevated concentrations of metals, both from the original tap water and from industrial processes [Kharko & Danilov, 2025]. Common contaminants include iron, manganese, zinc, copper, nickel, and chromium. Particularly stringent quality standards are established for the water bodies used for fisheries, which often require the use of highly effective treatment methods [SanPiN, 2021].

Among the promising approaches to wastewater treatment for heavy metals, electroflotation stands out. It is based on the separation of gaseous products of water electrolysis (hydrogen and oxygen), adsorption, and the floating of hydrophobic particles of pollutants in hydrogen and oxygen bubbles [Petrov et al., 2023]. The process is characterized by high efficiency in removing undissolved particles, compact equipment, the possibility of full automation, and the absence of reagent requirements [Shunkevich et al., 2025]. Heavy metal extraction is possible, but the effectiveness of the process will depend on the quantitative and qualitative composition of pollutants in the wastewater [Lobacheva et al., 2020].

Furthermore, the efficiency of water purification from various contaminants using electroflotation may be affected by processes of the electrode passivation—the formation of an oxide film on the metal surface that prevents the formation of gas bubbles. The results of a study [Akarsu et al., 2021] demonstrate the high efficiency of electroflotation for removing microplastics, which is typical for large supramolecular particles, but do not consider the passivation of aluminum and iron electrodes.

A study by Abdollahi et al. [2023] also discussed passivation in wastewater, noting that this phenomenon should be studied for specific types of wastewater based on their chemical composition. Abdollahi et al. [2023] did not disclose the specifics of the electrodes used, but instead focused on studying current conditions. The same study by Akarsu et al. [2021] examined distilled water and tap water as electrolytes, but since electrolytic properties are determined by the substances contained in the water, it was necessary to use real wastewater in the study.

The results obtained by Brodskiy et al. [2021] noted the rapid solubility of iron and aluminum electrodes and secondary water contamination during the purification process. Furthermore, the study results indicate a slowdown in the electroflotation process in the presence of salts in the electrolyte, indicating the need to study the electrolytic properties of the water in question.

Soliz et al. [2024] described the occurrence of pitting corrosion – a localized type of destruction of passive metals (stainless steel, aluminum), in which deep ulcers or cavities (pitting) form on the surface, leading to penetrating damage. The main cause is the disruption of the protective oxide film by activator ions (chlorides, bromides), which are typically present in high concentrations in seawater, which was studied in this article. It is worth noting that the study involved electrodes made of alloy Ti Gr 2, but stainless steel and titanium coated with ruthenium oxide have not been studied.

A large study conducted by Jima et al. [2023] was carried out on electroflotation with iron-based electrodes for the removal of heavy metals from electroplating wastewater. However, the process results in high electrode consumption due to iron dissolution, confirming the secondary contamination of the water, and this approach will not ensure fishery-grade quality of the purified water.

Jiang et al. [2023] examined water purification using ruthenium oxide electrodes, but proposes applying the treatment to microalgae, not heavy metals.

Diffusion control exists—an effect in which the flotation rate is limited by the ability of pollutant particles in the water to diffuse to the surface of the formed bubbles, or conversely, by the ability of bubbles to reach the pollutant particles. The results of study by Sebastián et al. [2017] pointed out a fundamental drawback of existing models: they ignore the overlap of diffusion zones. According of Mamme et al. [2017], this effect is examined for a specific water quality, and the authors generally note the need to study and account for this effect in each specific case.

A study by Palomar-Pardavé, [2005] explained the need to determine current density parameters and processing time when studying the electroflotation of water of a specific quality.

Anodic polarization is also of great interest for study. Anodic polarization is a phenomenon in which a current source connected to the anode begins to draw electrons from the metal atoms of the anode, inducing a positive charge in them and facilitating their transition from the crystal lattice into solution. This process leads to gradual dissolution of the anode and secondary water pollution [Akarsu et al. 2021].

The aim of this study was to experimentally substantiate the feasibility of removing heavy metals from industrial wastewater generated during abrasive waterjet cutting using electroflotation to meet standards established for fishery water bodies. To achieve this goal, the following objectives were addressed in this study: the influence of anodic polarization and passivation on gas formation and secondary water pollution; the role of diffusion control in limiting the rate of pollutant mass transfer; optimal conditions (current density, processing time), and selection the electrode materials to ensure maximum metal extraction with minimal energy consumption.

MATERIALS AND METHODS

The object of the study was industrial wastewater generated at the production site of a mechanical engineering enterprise. Sampling was carried out over the course of one year. Chemical analysis was performed using inductively coupled plasma atomic emission spectrometry (ICP-AES) on an ICPE-9000 spectrometer in accordance with the certified M-02-1109-08 method [M-02-1109-08. 2008].

To assess the distribution of metals by species, some samples were filtered through membrane filters with a pore diameter of 0.45 µm. The filtrates were acidified with concentrated nitric acid for preservation.

A comprehensive analysis of the enterprise's production facilities revealed that the primary sources of wastewater were waterjet metal cutting machines. The cutting technology utilizes high-pressure water with garnet sand added as an abrasive. The resulting wastewater enters holding tanks, where it settles under continuous flow and is then sent to the sewer system [Shtripling & Turenko 2005]. To determine the sources of manganese, X-ray spectral analysis of the garnet sand used in the process was conducted. The analysis was performed using an X-ray fluorescence spectrometer.

A laboratory electroflotation unit was designed for the study. The design was based on the principles outlined in [Kolesnikov et al., 2007] and adapted to specific conditions. The unit includes:

- 15-liter glass housing;
- block of vertically oriented electrodes (titanium cathodes, stainless steel anodes (which was later recognized as a mistake, despite the chemical neutrality of stainless steel), subsequently replaced with titanium with a ruthenium oxide coating);
- block of horizontally oriented mesh electrodes;
- circulation pump with flow rate control;
- DC power source with adjustable voltage and amperage (up to 72 V, up to 20 A);
- system for collecting the froth product (flotation concentrate).

The experiments were conducted in both flow-through and circulation modes. Samples were collected at fixed time intervals (5, 8, 10, 12, 15, and 20 minutes). Temperature, pH, and current load were monitored.

The required purification efficiency was calculated as the ratio of the difference between the initial concentration and the limiting concentration to the initial concentration. The current density was determined using Ohm's law, taking into account the geometric area of the electrodes.

Electroflotation is a promising approach to wastewater and process solution treatment, due to its high process speed and the intensive separation of the dispersed phase into a foam product. The extraction of suspended and colloidal particles occurs as a result of their adsorption to H_2 and O_2 gas bubbles formed on electrodes when a direct electric current is passed through the wastewater [Rudzisha et al., 2022]. Aggregates of gas bubbles containing particles float to the surface, forming a foam layer (flotation concentrate), which is removed by a scraper into a sludge collector [Petrova et al., 2022]. Individual soluble compounds that are physically adsorbed on particles are also taken out here (Figure 1).

Electroflotation can be performed using either soluble anodes or anodes made of insoluble materials. Electroflotation with soluble anodes is called electroflotation coagulation [Sverchkov & Gvozdetskaya, 2024]. Electroflotation provides high efficiency in removing contaminants in the form of suspended solids, suspensions, and emulsions from wastewater, as well as partial mineralization of organic compounds [Wang et al., 2021]. Depending on the physicochemical properties of the treated water and the phase-dispersed state of the extracted substances, electroflotation is typically preceded by neutralization of acidic or alkaline components, conversion of substances into insoluble compounds, coagulation, or flocculation to achieve the desired purification efficiency [Palomar-Pardavé et al., 2005].

This raises a number of questions that significantly influence the rationale for using electroflotation over, for example, reverse osmosis, the main drawback of which in this case is the potential for rapid fouling of filter membranes, requiring more frequent membrane replacement and maintenance of the entire treatment equipment. An electroflotator with insoluble electrodes is a kind of automated system, requiring only the disposal of flotation sludge, which does not require any downtime [Brodskiy et al., 2023].

However, if the desired purification efficiency cannot be achieved with the existing composition and properties of the wastewater and pretreatment is required, including pH adjustment, filtration, the addition of flocculants or electrolytes, and the conversion of metal compounds into insoluble forms, then the advantages of the electroflotation method—simplicity, convenience, and low cost of operation along with a high degree of purification—are significantly reduced [Singh, 2026]. Furthermore, due to its effectiveness in removing heavy metals, electroflotation is typically used in large-scale galvanic production facilities as one of the initial purification stages to significantly reduce concentrations. Subsequent stages, using other purification methods, bring the wastewater composition to regulatory limits. As a result, open sources report the high efficiency of electroflotation for wastewater treatment of heavy metals only in the concentration range of 50 to 500 mg/dm³.

All stages are mandatory for the process to proceed. Purification efficiency is affected by the physicochemical parameters of the system, the geometric dimensions of the apparatus, the electrical treatment mode, the initial metal concentration, pH, the nature and concentration of background electrolytes, and the presence of organic compounds [Sverchkov & Povarov, 2024].The

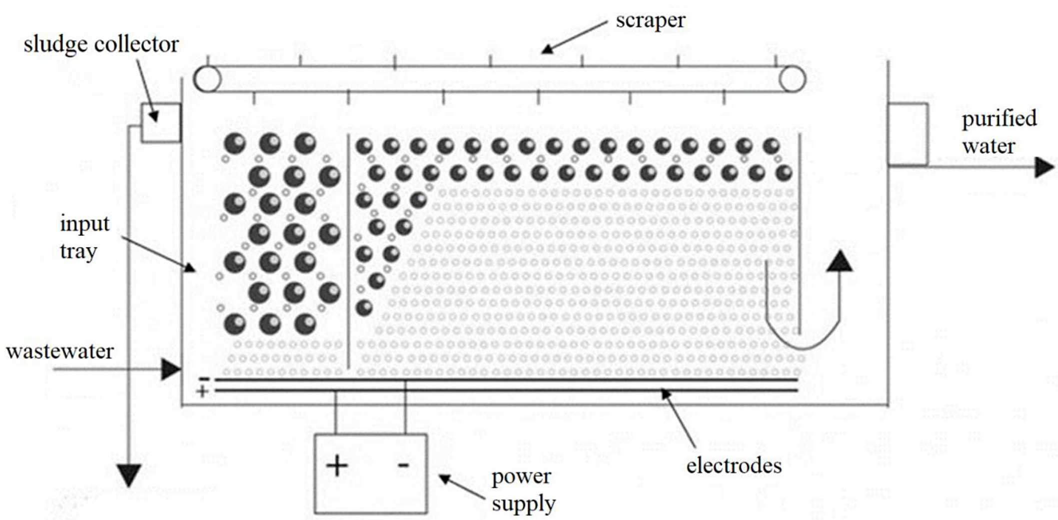

Figure 1. Operating principle of the electroflotation unit

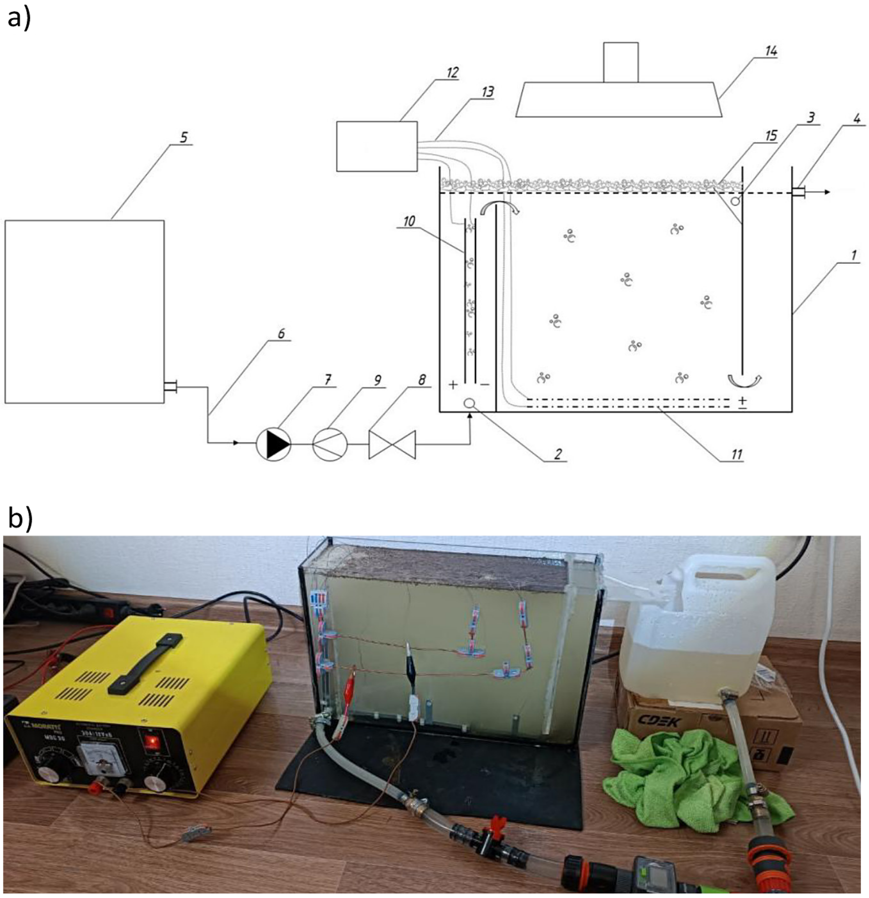

Figure 2. Diagram of the experimental electroflotation unit: (a) scheme, (b) photo of the unit
1 – electroflotator body; 2 – connection for feeding purified water; 3 – connection for removing flotation concentrate; 4 – connection for discharging purified water; 5 – container with feed water; 6 – PVC hose; 7 – circulation pump; 8 – shut-off valve; 9 – flow meter; 10 – block of vertically oriented electrodes; 11 – block of horizontally oriented electrodes; 12 – DC power source; 13 – current leads; 14 – exhaust; 15 – foam collector

electroflotation unit is shown on Figure 2 [Russian Patent 2853498 2025].

The initial design of the electroflotator unit included a body made of 5 mm thick monolithic polycarbonate, eight electrodes measuring 10×10 cm, and a 12–30 V power supply. However, when filled with water, the body deformed and started leaking, which required replacing the material with glass. The key challenge in the initial phase of research was the inability to achieve the estimated current load of 300 A/m² (10 A with an electrode area of 0.1 m²). The actual current did not exceed 1.5 A. During the debugging process, various power sources and electrode configurations were tested.

RESULTS AND DISCUSSION

The results of the industrial wastewater analysis are presented in Table 1. The data indicate a consistent excess of the standard values for iron, manganese, zinc and copper content throughout the entire observation period.

During independent sampling from the river from which water is taken for the needs of the enterprise, excess levels of some metals were detected (Table 2).

Thus, due to the elevated geochemical background of this region, unsatisfactory water treatment, and deterioration of the water supply network, the water used is characterized by the presence of exceedances of standard indicators for the content of metals, such as Fe, Zn, and Cu.

The maximum recorded concentrations were: Fe – 4.58 mg/dm³ (91.6 times the fishery maximum permissible concentration), Mn – 0.129 mg/dm³ (2.58 times), Zn – 0.085 mg/dm³ (1.7 times), and Cu – 0.0562 mg/dm³ (11.24 times).

The required purification efficiency, calculated based on the maximum concentrations, was: Fe – 98.91%, Mn – 61.24%, Zn – 41.18%, and Cu – 91.10%.

Table 1. Properties and average composition of wastewater discharged from the production site

Indicator	Concentration in discharged water, mg/dm³	Fishery maximum permissible concentration, mg/dm³
Suspended solids	9 ± 2	10
BOD_5	2.0 ± 0.7	2.1
COD	25.0 ± 0.7	30
Total nitrogen	0.10 ± 0.02	0.242
Petroleum products	0.0026 ± 0.0250	0.05
Phenols	0.0008 ± 0.0002	0.001
S^{2-}	0.0030 ± 0.0001	0.005
SO_4^{2-}	<50	100
Cl^-	270 ± 2	300
Al	0.0351 ± 0.0046	0.04
Fe	3.1 ± 0.341	0.05
Mn	0.129 ± 0.017	0.05
Cu	0.0562 ± 0.0089	0.005
Zn	0.085 ± 0.026	0.05
Cr(III)	0.010 ± 0.002	0.07
Cr(VI)	<0.005	0.02
Ni	0.005 ± 0.001	0.01
Cd	<0.005	0.01
Pb	<0.005	0.01
As	<0.005	0.01
Hg	<0.005	0.0001

Note: Temperature: 16.3 ± 0.2 °C, pH: 7.53 ± 0.10.

Table 2. Concentrations of metals in the river

Sample	Cu, mg/dm³	Fe, mg/dm³	Mn, mg/dm³	Zn, mg/dm³	Ni, mg/dm³	Cr(total), mg/dm³
1	0.015 ±0.002	1.26 ±0.14	0.033 ±0.03	0.086 ±0.026	0.0075 ±0.0009	0.010 ±0.002
2	0.0049 ±0.0007	0.49 ±0.05	0.026 ±0.003	0.026 ±0.008	0.0045 ±0.0006	0.0026 ±0.0008
3	0.0037 ±0.0006	0.724 ±0.079	0.0087 ±0.0011	0.017 ±0.005	0.0013 ±0.0002	0.0021 ±0.0007
4	0.027 ±0.004	1.10 ±0.12	0.0218 ±0.0028	0.110 ±0.033	0.0017 ±0.0002	0.019 ±0.006
5	0.0100 ±0.0016	0.66 ±0.07	0.0341 ±0.0044	0.050 ±0.015	0.00030 ±0.00004	0.004 ±0.001
6	0.0031 ±0.0005	1.89 ±0.21	0.0078 ±0.0010	0.071 ±0.021	0.0009 ±0.0001	0.010 ±0.003
Fishery maximum permissible concentration	0.005	0.05	0.05	0.05	0.01	0.02

Analysis of the tap water entering the facility (Table 3) revealed that certain metals exceeded their maximum permissible concentrations even before their use in technological processes. This indicates the contribution of external factors to wastewater pollution. The distribution of metals by species is crucial for selecting a purification method. The study results are presented in Table 4.

As it can be seen from the presented data, the majority of heavy metals are in undissolved form and can theoretically be removed by flotation methods. The content of dissolved metals, taking into account measurement error and background values, is close to the maximum permissible concentrations for the corresponding elements. This suggests that purification can be effectively implemented without prior conversion of metals into insoluble forms using reagents.

The waterjet cutting machine was used for the processing of incoming workpieces made

Table 3. Metal concentrations in tap water

Indicator	Concentration of pollutants in discharged water, mg/dm³	Maximum permissible concentration, mg/dm³
Cr(total)	0.0075±0.0016	0.02
Fe	0.266±0.029	0.05
Cu	0.0064±0.0010	0.005
Mn	0.0215±0.0028	0.05
Zn	0.074±0.022	0.05
Ni	0.0045±0.0006	0.01

Table 4. Content of heavy metals in water in various forms

Form	Cu, mg/dm³	Fe, mg/dm³	Mn, mg/dm³	Zn, mg/dm³
Dissolved	0.0036±0.0006	0.0385±0.0042	0.0078±0.0010	0.0112±0.0034
Undissolved	0.0191±0.0031	0.5685±0.0625	0.0638±0.0083	0.0968±0.0290
Gross	0.0227±0.0036	0.607±0.067	0.0716±0.0093	0.108±0.032
Background	0.0010±0.0002	0.013±0.001	0.049±0.006	0.0075±0.0023
Dissolved-Background	0.0026±0.0008	0.0255±0.0052	0.0412±0.006	0.0037±0.0057
Gross-Background	0.0217±0.0038	0.594±0.068	0.0226±0.0153	0.1005±0.0343
Fishery maximum permissible concentration	0.005	0.05	0.05	0.05

of high-alloy structural steel grade 14X17H2, 36X2H2MΦA, 38XH3MΦA (Russia), X20CrNi17-2, 34CrNiMo6, 34NiCrMoV14-5 (European Union), AISI 431, AISI 4340 (USA) in which the main alloying elements are Cr, Ni, and Mn. The composition of the garnet sand was determined using X-ray spectral analysis. The content of Fe was 220.3±2.1 g/kg, Mn — 3.916±0.413 g/kg, Ti — 0.084±0.010 g/kg, Sr — 0.025±0.002 g/kg, Ca — 54.5±2.1 g/kg, K — 7.89±1.17 g/kg revealed a high content of Mn (3.916 g/kg), which allows explaining the excess of Mn in wastewater by the products of destruction of abrasive material.

Thus, a complex contamination picture emerged: the initial influx of iron, copper, and zinc from tap water was supplemented by manganese contamination from abrasive degradation and additional iron from wear of the metal being processed. The next stage of the work was the development, design, and commissioning of an electroflotation unit. Experiments revealed that achieving the required current density required:

- increasing the electrode area (each additional electrode increases the current by approximately 1 A);
- using higher voltage (>50 V) to overcome anode passivation;
- using titanium anodes with a ruthenium oxide coating instead of stainless steel.

When using stainless steel anodes, active corrosion, metal dissolution, and secondary contamination of the treated water were observed (Table 5). It shows, during electrical treatment, metal concentrations increased, rather than decreased, indicating electrode dissolution. The electrodes became coated with traces of corrosion, and the water acquired a reddish tint due to the dissolution of iron compounds (Figure 3).

According to preliminary test results, electrode passivation can significantly impact the

Table 5. Results of analysis of anode corrosion

Sample	Fe, mg/dm³	Mn, mg/dm³	Zn, mg/dm³
Original	0.367±0.040	0.0206±0.003	0.131±0.039
5 minutes of processing	1.741±0.191	0.0391±0.005	0.132±0.040
10 minutes of processing	3.082±0.339	0.0543±0.007	0.131±0.039
15 minutes of processing	2.996±0.329	0.0441±0.006	0.095±0.028
Fishery maximum permissible concentration	0.05	0.05	0.05

a) b)

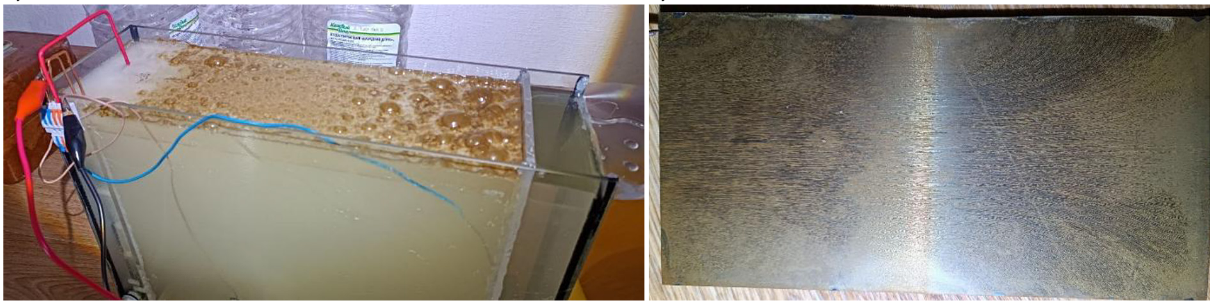

Figure 3. Reddish-colored foam formed during the operation of the electroflotator (a), not related to the composition of the water, and traces of corrosion on the stainless steel anode (b)

efficiency of the electroflotation process. The phenomenon of titanium anode passivation required further study. During passivation, an oxide film with dielectric properties forms on the anode surface (Figure 4). The electrochemical reaction rate, initially reaching peak values, then drops to near zero, causing anodic concentration polarization. This occurs because, as the electrochemical reaction proceeds, an oxide film forms on the anode surface, the concentration of reactants on the anode surface decreases, and the concentration of reaction products increases. The resulting concentration gradient hinders further progression of the process.

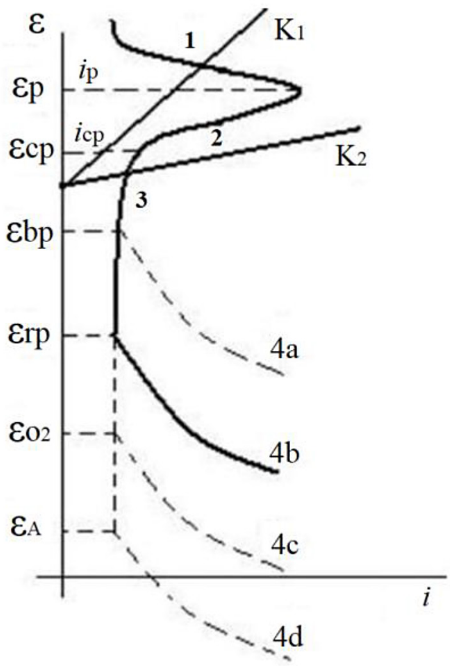

Figure 4. Anodic polarization curve for a passivated metal: ε_p – potential of the beginning of passivation, ε_{cp} – potential of complete passivation, ε_{bp} – breakdown potential, $\varepsilon_{ПЕР}$ – repassivation potential, ε_{O2} – potential of oxygen evolution, ε_A – anodizing potential, i_p – passivation current density, i_{cp} – current density of complete passivation, K_1, K_2 – cathodic curves

At relatively high current densities, the polarization process occurs within one to two seconds, while at minimal current densities, it takes several minutes. A "breakdown" voltage across the oxide layer is required to maintain the reaction. Experiments have shown that at voltages below 30 V, the reaction subsides within 1-2 minutes; stable electrolysis is observed at voltages above 50 V.

The electrode material also has a significant impact on water composition. It has been established that the anode should be titanium coated with ruthenium oxide [Jiang et al., 2023]. Upon oxidation, this forms a thick passivating oxide film, but upon reaching the oxygen evolution potential, the film "breaks down" and intense gas formation begins [Berkinbayeva et al., 2022; Nyein et al., 2024]. Unlike stainless steel, titanium with a ruthenium oxide coating is not subject to corrosion and does not contaminate the purified water with its own dissolution products.

Like the electrode material, the electrolyte composition affects the process efficiency [Aung et al., 2024; Mangarengi et al., 2025]. Electrolyte composition significantly influences the efficiency of the electroflotation process. Primarily, this influences electrical conductivity, which determines the generation of gas bubbles on the electrodes. Low electrical conductivity leads to a decrease in the intensity of electrolysis and a reduction in the number of bubbles formed [Aung et al., 2025].

Electrodes are known to corrode during electroflotation [Biswas et al., 2025; Medvidović et al., 2023]. Experiments have shown that the oxide film formed on the surface of stainless steel and titanium is unstable to sulfates and, especially, chlorides, which can locally penetrate the protective layer, causing pitting corrosion (Figures 5 and 6) [Latypova et al., 2018]. This leads to the secondary contamination of the purified water, degradation, and through-corrosion of the electrodes [Tang et al., 2025].

During operation, titanium conductors can overheat (Figure 7). An additional problem was overheating of titanium conductors at current densities above 420 A/m² (15 A) due to the low electrical conductivity of titanium. At operating voltage and current, the titanium wire overheated and melted, breaking at its weakest points—in air at the bending points [Elo et al., 2017]. This limited the upper limit of the installation's operating parameters.

There is an effect called diffusion control [Abyaneh, 2006; Luo et al., 2018; Sebastián et al., 2017]. The limitation of the electrochemical reaction due to the limitations in electrolyte diffusion is called diffusion control. The ions required for electrochemical reactions (gas formation at the electrodes) must diffuse to the electrodes [Mamme et al., 2017; Barrera-Díaz et al., 2014]. However, if the diffusion rate is low, this leads to a decrease in current and a reduction in the rate of gas bubble formation [Luo et al., 2022].

Initially, due to the similarity between the effects of diffusion control and anodic polarization, suspicion fell on the former option. However, the volt-ampere characteristic in this case

Figure 5. Traces of pitting corrosion on a stainless steel electrode

Figure 6. Traces of corrosion (TiO_2) on a titanium anode with a ruthenium oxide coating

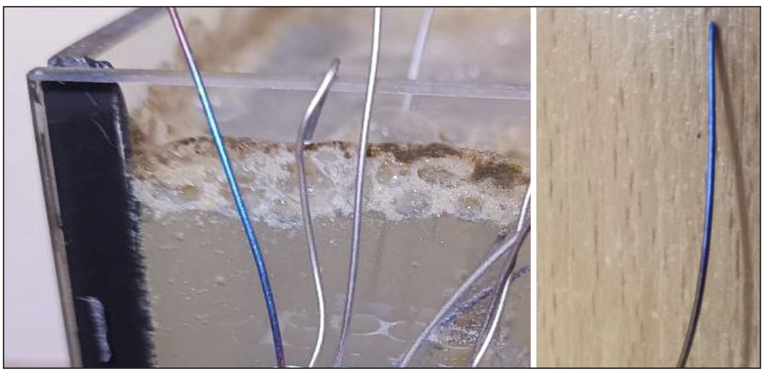

Figure 7. Traces of overheating on current leads made of titanium

would have only one extreme, and the voltage as well as current parameters would change smoothly over time, unlike anodic polarization. However, under the conditions of high current density, relative water purity and, consequently, low electrical conductivity, as well as slow water exchange, this problem may manifest itself in the future.

A key component of the development of a laboratory electroflotation system is the optimization of electroflotation purification parameters. After refining the design and operating modes of the system, final experiments were conducted, the results of which are presented in Table 6.

The required degree of purification is achieved after 20 minutes of water treatment in the electroflotator. With a chamber volume of 15 liters, this corresponds to a flow rate of 0.75 l/min. The optimal process parameters were:

- current density – 420 A/m² (14 A with an electrode area of 0.1 m²),
- voltage >50 V,
- processing time – 20 minutes,
- temperature – unadjusted (natural heating to 25–30 °C),
- pH – unadjusted (initial 7.53 ± 0.10).

It should be noted that to achieve the required efficiency, the current density had to be increased from the calculated 300 A/m² to 420 A/m². Further increases in current density (over 15 A) resulted in intense corrosion of the titanium electrodes, forming a white titanium oxide deposit.

The obtained results confirm the fundamental feasibility of removing heavy metals from industrial wastewater using electroflotation without the use of reagents or additional pH adjustments. The purification efficiency achieved in the experiments exceeds 98% for iron, 99% for manganese, 98% for copper, and 88% for zinc.

It was established that the critical factors determining the success of the process are:

- the form of metals in the wastewater – the predominance of undissolved forms ensures effective flotation;
- the electrode material – the use of titanium anodes with a ruthenium oxide coating eliminates secondary contamination;
- the electrical parameters – high voltage is required to overcome anode passivation.

The identified electrochemical phenomena (passivation, polarization, corrosion) are characteristic of the processes using insoluble electrodes and require careful monitoring. The phenomenon of anodic polarization of passivated metals deserves special attention; it can only be overcome by achieving the oxygen evolution potential of the material.

A comparative analysis of the obtained data with literature sources [Kulsky et al., 1978] showed that the efficiency of electroflotation purification at low metal concentrations (less than 50 mg/dm³) has been insufficiently studied. Most studies have focused on concentrated solutions from galvanic production [Smirnov et al., 2023]. This study bridges this gap by demonstrating the applicability of the method for the post-treatment of water with relatively low levels of contamination [Smirnov & Suchkova, 2019; Eremeeva et al., 2026].

Importantly, the experiments did not require the addition of flocculants, coagulants, or pH adjustment [Matveeva et al., 2024]. This significantly simplifies the process flow diagram and reduces operating costs compared to reagent methods, the efficiency of which typically does not exceed 60% [Borisova et al., 2025], as well as membrane methods, which require frequent replacement of filter elements. This property will be especially relevant when using electroflotation in water purification processes and in specific processes that do not allow the introduction of foreign impurities [Eremeeva et al., 2025; Orekhova et al., 2024; Strizhenok et al., 2019].

Table 6. Electroflotation purification results

Sample	Cu, mg/dm³	Fe, mg/dm³	Mn, mg/dm³	Zn, mg/dm³
Original	0.0517±0.0089	2.7930±0.3072	0.1251±0.0163	0.0085±0.0026
5 minutes of processing	0.1330±0.0213	0.7431±0.0817	0.0784±0.0125	0.0068±0.0021
10 minutes of processing	0.0417±0.0067	0.2430±0.0267	0.0163±0.0021	0.0054±0.0016
15 minutes of pocessing	0.0160±0.0026	0.0884±0.0097	0.0160±0.0021	0.0018±0.0005
20 minutes of processing	0.0018±0.0003	0.0014±0.0002	0.00030±0.00004	0.0010±0.0003
Fishery maximum permissible concentration	0.005	0.05	0.05	0.05

CONCLUSIONS

This study established that the industrial wastewater generated during hydroabrasive cutting of metals at a mechanical engineering plant is characterized by a consistent exceedance of fishery water quality standards for iron (91.6 times of the fishery maximum permissible concentration), manganese (2.58 times), zinc (1.7 times), and copper (11.24 times). The obtained results revealed that the main factors are: elevated background concentrations of metals in tap water (iron, copper, zinc), the hydroabrasive cutting process leading to additional iron input, and the destruction of garnet sand containing manganese in amounts of about 3.9 g/kg.

This work confirmed the fundamental feasibility of treating this wastewater by electroflotation without preliminary reagent precipitation, without pH adjustment, and without the introduction of flocculants. This is achieved because the majority of heavy metals are in an undissolved form and are effectively extracted by bubbles of electrolytic gases (hydrogen and oxygen). The optimal process parameters ensuring compliance with fishery maximum permissible concentration standards were: current density of 420 A/m², voltage above 50 V, and treatment time of 20 minutes. The achieved residual concentrations were: Fe – 0.0014 mg/dm³, Mn – 0.0003 mg/dm³, Zn – 0.0010 mg/dm³, Cu – 0.0018 mg/dm³, which corresponds to a treatment efficiency of 98–99% for most metals.

The typical results demonstrate high electroflotation efficiency at relatively high initial metal concentrations of 50–500 mg/dm³. However, the obtained results indicated the possibility of polishing low-concentration wastewater (<5 mg/dm³ for iron), showing that the method maintains an efficiency of over 98% even at such low pollution levels. This is particularly important for meeting stringent fishery standards. The conducted experiments with stainless steel anodes fully confirmed this effect; the iron concentration in water increased from 0.37 to 3.08 mg/dm³ within 10 minutes. The use of titanium anodes with a ruthenium oxide coating completely eliminated secondary contamination. The phenomenon of passivation of titanium anodes leads to a sharp drop in current; at voltages below 30 V, the reaction ceases within 1–2 minutes. It was experimentally established that stable process operation requires a voltage above 50 V, which corresponds to the oxygen evolution potential on titanium ("breakdown" of the oxide film), while the other studies recommended voltages (12–30 V) proved insufficient under our conditions.

This work established that under the conditions of relatively clean water and low electrical conductivity, the diffusion control effect may potentially manifest itself during process scaling. However, in experiment (unit volume of 15 dm³, circulation mode), the determining factor was anodic polarization, rather than diffusion limitations, since the studies demonstrated a sharp current drop characteristic of passivation, rather than the smooth change typical of diffusion control. High sensitivity of titanium electrodes to pitting corrosion in the presence of chlorides has been noted. The studied wastewater contained chlorides at a level of 270 mg/dm³, which is below the threshold of aggressive impact; however, traces of pitting corrosion were recorded during long-term experiments. The overheating of titanium current leads at current densities above 400 A/m², was found beacuse of the low electrical conductivity at currents exceeding 15 A.

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